University of Patras
Department of Mechanical Engineering & Aeronautics
Division of Energy, Aeronautics & Environment
Laboratory of Mechanical Engineering

ΣΠΟΥΔΑΣΤΙΚΗ ΕΡΓΑΣΙΑ

Mitigating the Urban heat island effect with Green Roofs-A review on benefits, construction, limitations, and sustainability.

ELLI SIDERAKI
1067247

Supervisor: Michalakakou Panagiota, Professor

PATRAS, [17/10/23]

University of Patras, Department of Mechanical Engineering &
Aeronautics
Elli Sideraki

The approval of the thesis does not imply the acceptance of the author's views. During the authorship, the principles of academic ethics have been respected.

Μετριασμός της Αστικής Θερμικής Νησίδας μέσω των Πράσινων Στεγών- Μια ανασκόπηση για τα οφέλη, την κατασκευή, τους περιορισμούς και τη βιωσιμότητα.

Έλλη Σιδεράκη

ΠΕΡΙΛΗΨΗ

Η αστικοποίηση έχει βελτιώσει δραστικά την ποιότητα ζωής των ανθρώπων, προσφέροντας, μεταξύ άλλων, ευκαιρίες για τεχνολογικές εξελίξεις, εκπαίδευση και ιατρική περίθαλψη. Ωστόσο, η ανάπτυξη μεγάλων και πυκνοκατοικημένων πόλεων ευθύνεται για τη δημιουργία ενός παγκόσμιου φαινομένου που ονομάζεται φαινόμενο «Αστικής Θερμικής Νησίδας» (ΑΘΝ). Η ΑΘΝ αναφέρεται στις διαφορές θερμοκρασίας που παρατηρούνται μεταξύ του εσωτερικού των αστικών περιοχών και των περί-αστικών περιοχών. Το φαινόμενο αυτό οφείλεται σε διαφόρους παράγοντες. Η εξάπλωση των αδιαπέραστων, γκρι επιφανειών, σε συνδυασμό με τη μείωση της βλάστησης εντός των πόλεων, είναι δύο από τους κύριους μοχλούς των ΑΘΝ. Οι ΑΘΝ έχουν πολλές αρνητικές επιπτώσεις τόσο για το περιβάλλον όσο και στην ανθρώπινη υγεία, γεγονός που καθιστά την αναζήτηση μέτρων αντιμετώπισης τους πολύ σημαντική. Αξίζει να σημειωθεί ότι η αύξηση του πράσινου και η εγκατάσταση φυτεμένων δωμάτων εντός των πόλεων είναι δύο από τα πιο αποτελεσματικά μέτρα για τη μείωση του φαινομένου της ΑΘΝ. Το παρόν σύγγραμμα αναλύει περαιτέρω τις αιτίες, τις αρνητικές επιπτώσεις και τις στρατηγικές μετριασμού του φαινομένου των ΑΘΝ, εστιάζοντας στη συνέχεια στις δομές των πράσινων στεγών.

Οι πράσινες στέγες είναι εξειδικευμένα συστήματα που υποστηρίζουν την ανάπτυξη βλάστησης στις οροφές διατηρώντας την ακεραιότητα της υποκείμενης δομής. Η ιδέα της κάλυψης δωμάτων από φυτά έχει υιοθετηθεί από την αρχαιότητα. Οι πράσινες στέγες προσφέρουν, μεταξύ άλλων, πολλά περιβαλλοντικά και ενεργειακά οφέλη. Ενισχύουν την αστική αισθητική και βιοποικιλότητα, μειώνοντας παράλληλα την ατμοσφαιρική ρύπανση. Επιπλέον, είναι ιδιαίτερα αποτελεσματικές στη διαχείριση των όμβριων υδάτων, στη βελτίωση

της ποιότητας του νερού και στη μείωση της ηχορύπανσης. Από ενεργειακής άποψης, οι πράσινες στέγες συμβάλλουν στη μείωση της κατανάλωσης ενέργειας τους καλοκαιρινούς κυρίως μήνες, παρέχοντας σκιά και ψύξη. Ως αποτέλεσμα συμβάλλουν στη μείωση του κόστος που σχετίζεται με τη διαχείριση των όμβριων υδάτων, τη θέρμανση και την ψύξη των κτιρίων. Οι πράσινες στέγες ταξινομούνται σε τρεις κατηγορίες: εκτατικές, εντατικές και ημιεντατικές. Κάθε πράσινη στέγη αποτελείται από πολλαπλά στρώματα, καθένα από τα οποία εξυπηρετεί μια συγκεκριμένη λειτουργία. Όλα αυτά τα στρώματα καθώς και οι προκλήσεις σχετικά με την εφαρμογή τέτοιων δομών αναλύονται στο παρόν σύγγραμμα. Τέλος, επισημαίνονται ερωτήματα σχετικά με το περιβαλλοντικό αποτύπωμα και τη σημασία της διερεύνησης ως προς τη βιωσιμότητάς των πράσινων στεγών.

Λέξεις κλειδιά
[αστική θερμική νησίδα, φυτεμένα δώματα, πράσινες στέγες, βιωσιμότητα, ανάλυση κύκλου ζωής]

Mitigating the Urban heat island effect with Green Roofs-A review on benefits, construction, limitations, and sustainability.

Elli Sideraki

ABSTRACT

Urbanization has drastically improved the life quality of humans, by offering, among others, technological advancements, educational, and medical opportunities. However, the development of such large and densely populated cities has also been responsible for the creation of a worldwide phenomenon called the “Urban Heat Island” effect (UHI). UHI refers to the temperature differences between urban areas and their surrounding natural environment and is caused by a combination of various factors. The expansion of impermeable, low albedo surfaces, along with the reduction of natural vegetation, are two of the main drivers of UHIs. UHIs have many negative impacts on both the environment and human health, which makes research for mitigation measures very important. It is worth noting that implementing green infrastructures and increasing vegetation within the cities are the most effective measures for reducing the UHI effect. This paper further analyses the causes, negative effects, and mitigation strategies of the UHI effect and subsequently focuses primarily on green roofs.

Green roofs are specialized systems that support plant growth on rooftops while maintaining the integrity of the underlying structure. The idea of covering roof tops with vegetation dates to ancient times. Green roofs offer, among others, various environmental and energy benefits. They enhance urban aesthetics and urban biodiversity as well as reduce air pollution. On top of that, green roofs are especially effective at managing stormwater, improving water quality, and reducing noise pollution. From an energy perspective, green roofs help reduce energy consumption in the summertime by providing shade and cooling effects. Economically, green roofs can also reduce costs associated with stormwater management, heating, and cooling. Green roofs are classified into three categories: extensive, intensive, and semi-intensive green roofs. Each green roof structure consists of multiple layers, each one serving a specific function in the green roof system, contributing to its durability, energy efficiency, and plant health. All the different layers of green roofs as well as several challenges and considerations regarding their implementation are listed in this paper. Lastly, questions concerning the environmental footprint of such structures as well as the importance of investigating their sustainability are also highlighted in this paper.

Key Words

[Urban heat island, green infrastructure, green roofs, sustainability, Life Cycle Assessment]

LIST OF TABLES

Table 1: Plant species suitable for green roof, their flowering seasons, the desired soil type and their final height [9]. 27

Table 2: Plant species suitable for Mediterranean [9]. 28

LIST OF FIGURES

Figure 1: Chart representation of the UHI effect [35]. 2
Figure 2: Negative effects of the UHI during summer and winter season [23]. 6
Figure 3: Yamamoto's 'wind path' proposal [24]. 8
Figure 4: The Hanging Gardens of Babylon [36]. 14
Figure 5: The California Academy of Sciences Living Roof – San Francisco, Calif., United States [21]. 16
Figure 6: ACROS Fukuoka Prefectural International Hall – Fukuoka City, Japan [21]. 17
Figure 7: The Vancouver Convention Center – Vancouver, BC, Canada [21]. 17
Figure 8: The Nanyang Technological University – Singapore [21]. 18
Figure 9: Chicago City Hall Green Roof - Chicago, Ill., United States [21]. 19
Figure 10: Extensive green roof [37]. 24
Figure 11: intensive green roof [37]. 25
Figure 12: Semi-intensive green roof [37]. 25
Figure 13: The structure of a green roof [21]. 26

SYMBOLS & ABBREVIATIONS

SYMBOLS & ABBREVIATIONS	MEANING
UHI	Urban heat island
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau
LECA	Lightweight expanded clay aggregates
ASTM	Association of Standards and Testing Materials
CAS	California Academy of Sieneses
LEED	Leadership in Energy and Environmental Design
LAI	Leaf area index
AFP	Air-filled porosity
WHC	Water holding capacity
BCA	Benefit-Cost Analysis
LCA	Life Cycle Assessment
°C	degrees Celsius
K	Kelvin
m	meters
cm	centimeters
dB	decibels

CONTENT TABLE

ΠΕΡΙΛΗΨΗ V
ABSTRACT VIII
LIST OF TABLES X
LIST OF FIGURES XI
SYMBOLS & ABBREVIATIONS XIII
CONTENT TABLE XV
1 URBAN HEAT ISLAND EFFECT 1
1.1 DEFINITION AND CHARACTERISTICS 1
1.2 CAUSES 3
1.2.1 Urban geometry 3
1.2.2 Low albedo materials 4
1.2.3 Human factor 5
1.2.4 Heating and Cooling demands 5
1.3 NEGATIVE EFFECTS 6
1.4 MITIGATION STRATEGIES 7
1.4.1 Urban planning 7
1.4.2 High albedo materials 8
1.4.3 Green vegetation and shade trees 9
1.4.4 Pervious pavements 10
1.4.5 Water bodies 10
1.4.6 Green Infrastructure 10
1.5 UHI IN GREECE 12
2 GREEN ROOFS 13
2.1 INTRODUCTION 13
2.2 HISTORY OF GREEN ROOFS 14
2.3 EXAMPLES OF MODERN GREEN ROOF SYSTEMS 15
2.4 BENEFITS 19
2.4.1 Environmental and Social benefits 20

2.4.2 Energy benefits 20
2.4.3 Air quality 22
2.4.4 Water retention 22
2.4.5 Noise reduction 23
2.4.6 Economic benefits 23
2.5 CLASSIFICATION OF GREEN ROOFS 24
2.6 COMPONENTS AND MATERIALS 25
2.6.1 Vegetation 26
2.6.2 Substrate layer 28
2.6.3 Filter layer 31
2.6.4 Drainage layer 31
2.6.5 Root barrier 32
2.6.6 Insulation layer 32
2.6.7 Waterproofing layer 32
2.7 FACTORS AFFECTING THERMAL PERFORMANCE 33
2.7.1 Thermal insulation 33
2.7.2 Evapotranspiration 34
2.7.3 Shading effect and heat flux 34
2.8 LIMITATIONS AND CONSTRAINS 35
2.8.1 Cost 35
2.8.2 Maintenance 36
2.8.3 Sustainability 36
2.8.4 Research on materials 37
2.8.5 Rooftop leakage 37
2.8.6 Ultimate disposal 37
3 GREEN ROOFS AND SUSTAINABILITY 39
3.1.1 Life cycle assessment 40
4 CONCLUSIONS 43
BIBLIOGRAPHY 45

1 URBAN HEAT ISLAND EFFECT

1.1 DEFINITION AND CHARACTERISTICS

Heat island is the most recorded aspect of climate change with the recordings spanning nearly a century [11]. The development of "*sprawling*" cities represents a fundamental departure from the natural environment. In many ways, urbanization has its merits, as it paves the way for improved living standards. Regrettably, urbanization also carries adverse environmental, social, and economic repercussions. One such concern is the emergence of *urban heat islands* (UHIs).

Urban Heat Island (UHI) is a worldwide concern jeopardizing the functionality and livability of our urban areas. This phenomenon is characterized by temperature variations between the constructed urban environment and the surrounding natural landscape. Research based on experiments conducted in over 400 cities worldwide indicates that UHI can result in temperature increases of more than 5°C, with some cases even witnessing urban heat island intensities exceeding 10°C. The repercussions of urban overheating are far-reaching, affecting energy consumption, public health, peak electricity demands, and the local economy. Elevated ambient temperatures lead to greater cooling needs in buildings and significantly elevate the risk of heat-related illnesses and mortality. Recent research exploring the interplay between global and local climate changes has revealed a synergistic relationship between the two, with local UHI intensity notably escalating during extreme climate events such as heatwaves [3].

The intensity of UHI can be gauged using either of two closely related metrics: urban skin temperature, which pertains to surfaces like pavements and buildings, or meteorological UHI, which pertains to air temperature. The UHI phenomenon can be visualized by charting a curve that spans from one edge of a city to the opposite side, graphically depicting the temperature fluctuations as one moves from the rural surroundings into the urban environment and then back to the rural areas. In this graphical representation, the 'island' is depicted as a prominent peak positioned at the center of the graph. This peak typically mirrors the contours of the city's-built structures and is flanked by steep declines on either side, marking the transition between urban and rural regions. This visual representation effectively highlights the significant temperature differential that our cities experience [3].

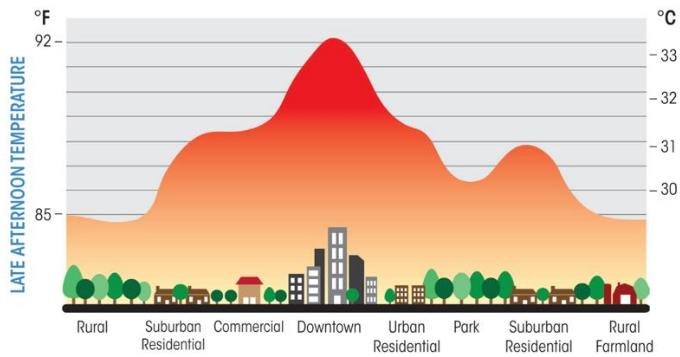

Figure 1: Chart representation of the UHI effect [35].

One significant feature is that UHI conditions are most pronounced on days and nights characterized by minimal cloud cover and light winds. Under these specific conditions, the temperature differences between urban areas and their non-urban surroundings reach their maximum value [2].

Another important feature of the UHI effect is the heightened nighttime temperatures, typically seen as the minimum daily temperatures. Urban areas exhibiting the UHI effect maintain warmth due to a combination of factors related to surface characteristics. The prevalence of materials like brick, concrete, asphalt, stone, and similar surfaces in urban settings leads to greater absorption of short-wave solar radiation during the daytime. In contrast, the surfaces more commonly found in sparsely populated suburban and rural regions, such as tree canopies, grass, and open fields absorb remarkably less solar radiation. The increased absorption of solar energy in urban areas results in a larger store of heat energy, which is then re-emitted less efficiently as long-wave radiation during the nighttime, compared to rural areas. This effect is exacerbated by the reduced vegetation cover in urban environments, as the absence of shade exposes these absorbent surfaces to direct sunlight. Furthermore, the lack of vegetative cover limits the potential for evaporative cooling in urban areas when compared to the typically leafier suburbs and rural landscapes [2].

Moreover, expansive metropolitan areas featuring multiple urban hubs experience an extended reach of UHI-related issues, which tend to be more pronounced than in smaller cities. To put it differently, these areas can witness simultaneous, heightened UHI levels occurring at various locations within the city. Additionally, the positions of these UHIs undergo shifts throughout the day [4]. One of the primary factors contributing to this dynamic phenomenon is the variation in urban geometry within different city blocks or neighborhoods. Depending on the urban layout, there can be disparities in both the quantity of heat generated and the duration it takes for this accumulated heat to dissipate [4].

1.2 CAUSES

The urban heat island phenomenon arises from a combination of various factors, primarily driven by human activities and urbanization. The main causes can be attributed to the modification of land surfaces and the alteration of the natural environment within cities. Furthermore, increase in energy consumption from air conditioning and industrial processes further amplifies UHIs [6]. The following paragraphs outline the key contributors or the UHI effect.

1.2.1 Urban geometry

Urbanization stands as the predominant catalyst behind the UHI effect. The steady expansion of impermeable, heat-absorbing surfaces, the growing density of our cities, and the diminishing presence of natural vegetation collectively constitute the primary drivers of the UHI phenomenon [1].

In urban settings, there are typically multiple layers of buildings. The heat radiated by one building is confined by the taller buildings in proximity, creating what is referred to as the urban canopy. Additionally, over the course of a day, urban structures absorb heat from sunlight, along with roads and other urban infrastructure, only to release it during the night [6]. Because of the high concentration of buildings, the speed of the wind is diminished, leading to a reduced cooling effect through convection. Consequently, the trapped heat cannot dissipate, intensifying its impact [23]. Furthermore, the layout and design of urban areas significantly influence the movement and dispersion of pollutants. The urban "Greenhouse effect" that raises the influx of long-wave radiation from the warmer, polluted urban atmosphere, contributes to heat retention. This phenomenon arises from the characteristic of greenhouse gases to strongly absorb infrared radiation within the electromagnetic spectrum. It's not limited solely to *carbon dioxide* (CO_2), other greenhouse gases like *methane* (CH_4), *nitrogen* (N_2), *ozone* (O_3), and *chlorofluorocarbons* (CFC_s) also play a role in this process. These gases absorb infrared energy within the wavelengths associated with the spectral window of water vapor. Consequently, when atmospheric CO_2 levels rise, it diminishes the atmosphere's transparency within this spectral window, strengthening the greenhouse effect [6].

In the context of urban heat islands, inadequate ventilation stands out as a primary contributor to the accumulation of heat. When pollutants settle in sheltered regions such as street canyons, they tend to linger for extended periods compared to rural areas, exacerbating the heat island effect. The canyon radiative geometry decreases the effective albedo of the system because of the multiple reflection of short-wave radiation between the canyon surfaces [6].

1.2.2 Low albedo materials

Additionally, the low albedo materials used in urban construction have reduced reflexivity as well as the capacity to store sensible heat, intensifying the heat buildup within the city [6]. *Albedo* is determined by assessing the proportion of solar energy that is reflected compared to the solar energy received. It is influenced by the composition of surfaces, materials, pavements, coatings, and so on. Albedo plays a direct role in shaping the local climate. When the albedo of urban surfaces is low, they absorb more solar energy, leading to an increase in urban temperature, essentially giving rise to the urban microclimate [23]. *Takebayashi* and *Moriyama* (2012) [1], in their examination of the surface heat budget of various pavement materials in Japan, demonstrated that regular asphalt can attain daytime temperatures up to 20°C higher than grass. The expanding network of buildings, paved surfaces and roadways within our cities has been proven to account for a substantial portion of elevated surface temperatures per unit volume when compared to any other man-made materials or structures [1].

1.2.3 Human factor

Because city centers offer a multitude of amenities, they tend to attract large concentrations of people, resulting in significant CO_2 emissions [23]. Therefore, anthropogenic heat generated by human activities and vehicles, increase pollution levels, and collectively contribute to the emergence of a distinct and transformed urban climate [1]. Today's cities continue to sprawl outward, a phenomenon aptly termed "*urban sprawl*." According to the United Nations Population Fund, cited in *Stempihar* et al. (2012) [1], it is projected that by 2030, 61% of the global population will reside in cities. The rapid growth of the world's population plays an important role in altering both the urban and global environments through phenomena such as global warming, biodiversity loss, and deforestation. This will substantially contribute to the UHI effect and further impact the environment as urban areas expand in size and density, green spaces diminish, and energy and cooling expenditures escalate [1].

1.2.4 Heating and Cooling demands

During the summertime, there is a growing trend of widespread air conditioner usage to ensure human comfort. While air conditioners effectively cool the interior of a building, they simultaneously produce an increased amount of heat [23]. In the context of today's densely populated cities, the prevalence of air conditioners required for maintaining comfortable indoor environments is notably higher. As our climate continues to heat up, the use of air conditioners becomes more widespread, consequently elevating the overall heat levels within a city. This not only leads to thermal discomfort but also results in heightened greenhouse gas emissions, thereby impacting human well-being [1].

1.3 NEGATIVE EFFECTS

As cities continue to grow and expand, the adverse impacts of UHIs on public health, energy consumption, and overall urban livability cannot be overlooked. The impact is particularly severe during the summer months, especially in tropical and arid regions, leading to discomfort for residents in the heart of the city [23]. One of the most glaring issues associated with the Urban Heat Island Effect is the uncomfortably hot weather it creates. Consequently, people often prefer seeking refuge in air-conditioned buildings rather than braving the heat outside. Paradoxically, while these buildings offer a cool oasis, the heat they extract is expelled into the surrounding outdoor air by air conditioning systems, effectively contributing to a rise in outdoor temperatures [7]. Additionally, Urban Heat Islands exacerbate air quality issues within cities. Air pollutants in these urban environments tend to rise along with the warm air and disperse towards the city's outskirts. However, they are subsequently trapped and forced back towards the city center by the surrounding cooler air, leading to a concentration of pollutants. Concerning water pollution, the intense heat absorbed by pavement and rooftops is transferred to stormwater, which then flows into storm sewers, elevating water temperatures as it enters streams, rivers, ponds, and lakes. These rapid temperature fluctuations can pose stress to aquatic ecosystems. While the problems of air and water pollution are pervasive in our modern world, their insidious nature lies in their constant circulation and accumulation. Such ongoing circulation can significantly endanger residents' health and diminish their overall quality of life. Consequently, finding solutions to combat the Urban Heat Island Effect has become a pressing concern for everyone [7].

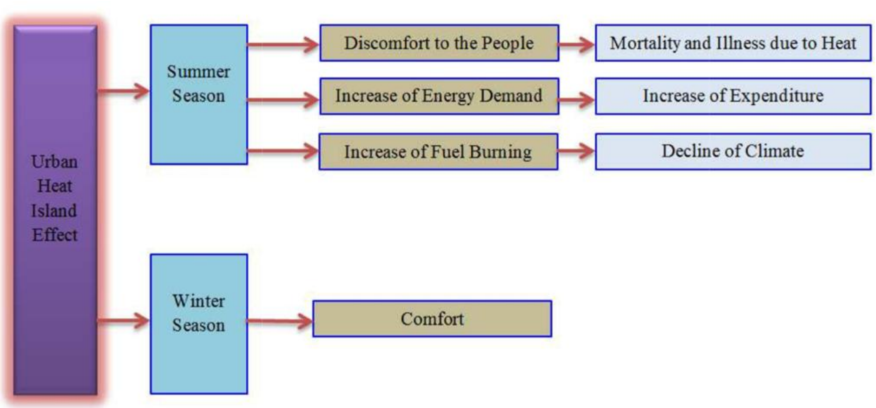

Figure 2: Negative effects of the UHI during summer and winter season [23].

1.4 MITIGATION STRATEGIES

Mitigation measures typically employ one of three strategic actions: decreasing the absorption of solar radiation within urban structures, improving the circulation of air throughout the city, and actively cooling specific components within the constructed environment, often achieved through processes like evapotranspiration and water evaporation [22]. In 2015, *Nuruzzaman* [22] proposed a list of eight strategies for UHI mitigation, which includes using highly reflective roofing and pavement materials, increasing green vegetation, planting shade trees, using permeable pavements, incorporating water features, adopting thoughtful urban planning, and implementing green roof systems. In 2009, *Giguère* [22] categorized UHI mitigation measures into four main groups: promoting vegetation and cooling (such as strategic tree and vegetation planting, greenifying parking lots, adding greenery around buildings, using green walls and roofs), implementing sustainable urban infrastructure (addressing design aspects of buildings, roads, and the overall built environment), adopting sustainable water management practices (including strategies like using trees and green roofs, installing permeable surfaces, creating rain gardens, retention ponds, infiltration trenches, dry wells, reservoir pavement structures, and using recycled water for pavement watering), and reducing anthropogenic heat (through measures like controlling heat production within buildings, reducing the number of vehicles in urban areas, and managing air conditioning demand via passive building design).

1.4.1 Urban planning

Effective urban planning and improvement of infrastructures such as parks, rivers, and roads, can also have a crucial impact on reducing the UHI phenomenon. For instance, "*wind paths*" utilize the natural airflow patterns within a locality to enhance urban ventilation [24]. In 2006, *Yamamoto* [24] proposed an urban planning strategy located along a riverbank. She suggests constructing buildings in a manner that facilitates the flow of cool air from the river into the city. When buildings are aligned parallel to the river, airflow into the city is hindered. Conversely, if buildings are placed at a 45-degree angle, they can channel wind effectively when it comes from one direction, but not when it comes from the opposite direction, trapping heat within the city. However, if buildings are positioned perpendicular to the river, airflow can occur. In different types of cities, having ample open space and wind channels can help minimize the impact of the urban microclimate.

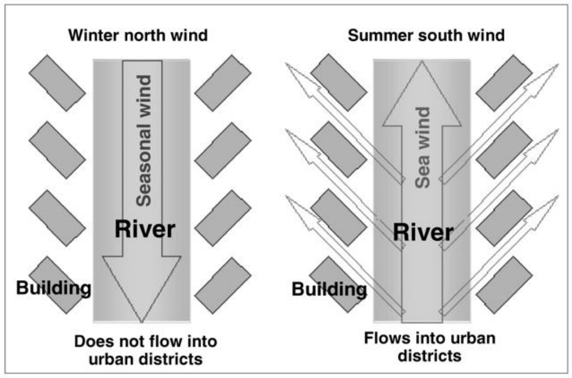

Figure 3: Yamamoto's 'wind path' proposal [24].

1.4.2 High albedo materials

Dark-colored roofs absorb heat from sunlight, leading to increased indoor temperatures in houses, while light-colored roofs, even with similar insulation properties, do not experience significant warming as they reflect solar radiation. Roofing materials with low albedo, which tend to absorb solar radiation, contribute to heat buildup in homes and subsequently higher energy consumption for cooling. Therefore, an effective solution would be to opt for roofing materials with high albedo. *Bretz* et al. (1998), *Akbari* et al. (1998) and *Konopacki* et al. (1997) [23] conducted studies that demonstrated the effectiveness of albedo by using roofing materials with varying albedo values ranging from 0.20 to 0.60. They found that a roof with an albedo of 0.60 led to a temperature reduction of 25°C compared to one with an albedo of 0.20. However, a drawback that associates with reflective roofs is that their reflective capacity reduces over time due to soot accumulation. Nevertheless, this issue can be easily addressed through periodic cleaning [23].

High albedo materials could also be used in pavements to reflect solar radiation and thus reduce the temperature of the streets. *Levinson* and *Akbari* (2002) [23] proposed the use of reflective concrete surfaces with albedo values ranging from 0.41 to 0.77. However, the effectiveness of employing high albedo materials for roadways and highway pavements may be limited due to factors like the sky view factor. Even if high albedo materials are used, some of the reflected sunlight would be blocked by surrounding buildings. Moreover, during most of the daytime, a significant portion of the pavement is covered by vehicles, reducing the impact of reflection. Additionally, the issue of glare associated with cooling roofs is also a concern with high albedo pavements. During the daytime, glare could have a detrimental effect on visibility. Furthermore, the wear and tear caused by vehicle traffic can quickly reduce the reflectivity of pavements. Therefore, before implementing such initiatives, it is essential to consider factors such as durability and visibility [23].

1.4.3 Green vegetation and shade trees

Trees play a significant role in mitigating the heat island effect through their process of evapotranspiration. In densely populated urban areas, where large human gatherings result in substantial CO_2 emissions and elevated temperatures, an increased presence of trees can aid in alleviating the situation by absorbing CO_2. According to *Theuwes* et al. [23], the temperature typically decreases by 0.6K for every 10% increase in vegetation. However, trees can obstruct the natural airflow within urban environments and consequently, the effectiveness of cooling breezes may be compromised.

Shade trees, characterized by their extensive canopy, offer shelter to buildings and pedestrians, shielding them from direct sunlight and thus maintaining a cooler environment. These trees also contribute to temperature reduction through the process of evapotranspiration. Their primary function is to intercept sunlight, thereby cooling buildings, reducing the need for air conditioning, lowering air temperatures, and enhancing air quality [23]. However, planting and maintaining shade trees entail costs and require several years of growth before they can effectively protect structures from intense heat. Furthermore, shade trees can be prone to damage during severe storms, posing risks to human safety. Additionally, the root systems of these trees can impact the foundations of neighboring buildings and streets, especially in densely populated regions like Bangladesh, India, and China [23]. Therefore, careful planning is essential before choosing to implement this technique.

1.4.4 Pervious pavements

Replacing impermeable pavements with pervious pavements, which allow water to penetrate, has the potential to significantly lower temperatures, due to evapotranspiration. The infiltration of water into these pavements will aid in keeping them cool, directly impacting the surrounding temperature [23].

1.4.5 Water bodies

An increased presence of water bodies can lead to temperature reduction through evaporation and the promotion of higher wind speeds. Furthermore, the high heat-absorbing capacity of water contributes to the cooling of urban areas. However, the findings from *Theuwes* et al.'s [23] bike traverse experiment contradict this notion. The explanation provided is that the elevated thermal inertia of water prevents nighttime cooling once it has absorbed heat, and stable nighttime conditions, which limit wind speed, might also play a role. Consequently, further investigation is necessary to determine whether the expansion of water bodies in urban areas genuinely contributes to temperature reduction or not.

1.4.6 Green Infrastructure

Green infrastructure is considered one of the most effective tools for mitigating the UHI effect. Examples of green infrastructure include green roofs (vegetation on rooftops for the collection and storage of rainwater), rain gardens (surface-level vegetation used to restore and facilitate the infiltration of rainwater), and permeable pavement (pavement designed with gaps to enable water infiltration) [30]. Such structures achieve this by lowering air and surface temperatures within urban areas through several mechanisms, including shading, heat removal from the air, and cooling the roof surface [25]. In this thesis a greater emphasis will be placed on green roofs.

Additionally, green roofs can substantially reduce surface temperatures and heat transfer, resulting in up to an 80% reduction in heat transfer through buildings on a typical summer day.

This reduction leads to a significant decrease in annual energy consumption [25]. As per Wong's research in 2005 [23], rooftops within urban areas account for approximately 21% to 26% of the total city area. Therefore, if these rooftops are transformed into green spaces with vegetation, it can play a significant role in combating the UHI effect.

An experiment conducted in a New York office building [11] involved the installation and simultaneous monitoring of three types of roofs: one white, one black, and one green. This monitoring spanned approximately a year. The findings revealed that, during the peak daytime hours, the surface temperature of the green roof was consistently 1 to 8 degrees Kelvin lower than that of the white membrane. Conversely, during the nighttime hours, the reflective membrane was 1 to 5 degrees Kelvin cooler than the green roof. These results lead to the conclusion that the green roof's potential to reduce sensible heat transfer during peak periods is significantly higher compared to that of the reflective membrane, making it a more effective option for mitigating the heat island effect.

Research was also carried out by *Chen* et al. (2009) in Tokyo [11] to assess the climatic impact of different mitigation techniques, including green roofs. The study considered extensive roofs planted with grass. The results indicated that when vegetative roofs were installed in medium and high-rise buildings, their ability to reduce ambient temperatures at street level was nearly negligible. Similar findings are presented in *Ng* et al. (2012) [11], where they assessed the climatic effects of installing vegetative roofs on 60-meter-tall buildings in Hong Kong and both intensive and extensive green roofs were considered. The study revealed that the potential reduction in street-level ambient temperature in this densely populated high-rise area was nearly negligible. The study's conclusion was that when the ratio of building height to street width (aspect ratio) exceeded 1, the cooling benefits at street level were minimal.

Because urban areas are expected to expand in the future, potentially at the expense of rural areas, it is particularly crucial to address the UHI effect and apply effective mitigation strategies. Among the options, the most potent solution lies in expanding green spaces and vegetation in the cities. Thus, increasing the urban vegetation as well as the widespread adoption of green infrastructure stand out as the most favored method for cooling urban environments [7].

1.5 UHI IN GREECE

The big cities of Greece experience the heat island effect, primarily due to rapid industrialization and urbanization in recent years. This effect is noticeable in both summer and winter. *Theodore M. Giannaros* et, al. (2013) [32] conducted a numerical study of the UHI over Athens, Greece. Based on the computer-generated model, Athens experiences significantly warmer nighttime air temperatures compared to its neighboring areas, with a difference exceeding 4 degrees Celsius. In contrast, the temperature variation is less pronounced in the early morning and midday hours. The most intense difference in canopy-level heat island intensity was observed in the early morning, while the maximum contrast occurred during the nighttime. *Michalakakou* et, al. (2001) [34] on a two-year study in Athens, Greece, utilized a neural network model to examine the influence of large-scale atmospheric patterns on the urban heat island effect. The model, using eight distinct synoptic atmospheric categories and four relevant meteorological factors, found that these large-scale atmospheric patterns significantly impact the heat island effect. High-pressure systems tend to enhance the heat island, while strong northerly winds prevent or diminish it. Additionally, *Papakostas* et, al. [33] calculated Heating (HDD) and Cooling (CDD) Degree Days for the greater metropolitan area of Thessaloniki. They found that the average HDD value in the city was 19% to 48% less than that of the surrounding locations. Conversely, the average CDD value in the city center was 10% to 40% higher than in the surrounding areas.

For the small to medium-sized city of Hania in Crete, *Kolokotsa, Psomas*, and *Karapidakis* (2009) [33] found a UHI intensity variation ranging from 0.6°C to 8°C, with an average value of 2.6°C. This variation was significantly influenced by wind speed and direction. In the case of the medium-sized city of Volos, *Papanastasiou* et al. (2010), *Papanastasiou* and *Kittas* (2012) [33] reported that the urban heat island effect reached 3.4°C during winter and 3.1°C during summer. In some instances, the intensity reached a maximum of 8°C, although this was mitigated by sea breezes near the shoreline, reducing the effect by approximately 4°C.

2 GREEN ROOFS

2.1 INTRODUCTION

Plants play a crucial role in climate regulation. They offer cooling benefits to urban environments, conserving energy. Trees provide shade for homes in summer, and their evapotranspiration lowers urban temperatures. Additionally, trees combat the greenhouse effect, filter pollutants, muffle noise, prevent soil erosion, and have a calming effect on people. Furthermore, vegetation's evapotranspiration can notably decrease urban temperatures, and tree shading is an effective means to reduce cooling energy consumption [8].

A green roof, also known as "*eco-roof*", "*living roof*" or "*roof garden*", is a specialized roofing system designed to support the growth of plants on rooftops while ensuring the structural integrity of the underlying roof [9]. The distinction between a regular bare roof and a green roof can be seen both in terms of quality and quantity. The way heat moves into a green roof is fundamentally different. As solar radiation, external temperature, and relative humidity traverse the vegetation on the roof, they undergo reductions. The plants, through their biological processes like photosynthesis, respiration, transpiration, and evaporation, absorb a significant portion of solar radiation. The solar radiation that isn't absorbed by the vegetation on the green roof is transformed into thermal energy, and it affects the indoor climate as it passes through both the garden component and the building structure of the roof [10].

Green roofs offer numerous benefits from ecological and social perspectives. They have a positive impact on the city's climate and surroundings, as well as the indoor temperatures of the buildings beneath them. Green roofs provide shade, reducing the impact of solar radiation, which is a major contributor to passive cooling. They also stabilize temperature fluctuations on the roof's surface and increase thermal capacity, helping to cool the spaces beneath during the summer. Additionally, green roofs offer significant environmental and human health advantages, such as mitigating the urban heat island effect, reducing energy consumption, improving air quality, and decreasing stormwater runoff. Effective thermal protection can significantly reduce the excessive heat absorbed by buildings in the summer. Plants on rooftops can provide this protection, offering an eco-friendly solution that not only lessens the thermal burden on building exteriors but also enhances densely populated urban areas with limited natural greenery [8].

2.2 HISTORY OF GREEN ROOFS

The history of green roofs began in ancient times. Such rooftop gardens were created to provide insulation and mitigate the negative effects of urbanization. The Hanging Gardens of Babylon, which dates back to around 500 BCE, was one of the most famous ancient green roof technologies. Nowadays, the idea of covering rooftops with vegetation has been adopted by many countries like Sweden, Finland, Iceland, Denmark, Norway, Greenland, Vinland, and the Faeroe Islands. Modern green roof systems have significantly evolved in comparison to ancient models, meaning that they are more improved, better designed and more effective.

Figure 4: The Hanging Gardens of Babylon [36].

The origins of modern green roofs trace back to the early 1960s during an energy crisis, when Germans began constructing green roofs to reduce energy consumption in buildings. Since then, Germany has become a global leader in green roof technology. By the early 1980s, the green roof market expanded rapidly in Germany. The *Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau* (FLL) published guidelines in German for constructing green roof systems. Up until today, more than 10% of buildings in Germany have implemented green roof systems, with green roof coverage increasing by approximately 13.5 million square meters annually [13].

While most of the research on green roofs has been conducted in Germany, Scandinavia, and Switzerland, the popularity of such structures has spread globally, with research, applications and innovations increasing. Guidelines for green roofs were released by the *Association of Standards and Testing Materials* (ASTM) in 2005 and 2006, providing detailed construction information. *FLL* published the latest guidelines for planning, execution, and maintenance. In 2009, the *USEPA* released a report explaining the green roof construction and benefits. The USA also conducted further research on green roof guidelines, implementation, and maintenance. Countries such as the USA, Canada, Singapore, Australia, Japan, China, Hong Kong, and South Korea are actively promoting the use of green roofs both in new and existing buildings to reap multiple benefits. Japan mandates green roofs for all new public and private buildings, with high fines applied to constructions that fail to follow the guidelines. In Portland, USA, 70% of new buildings' areas must incorporate green roofs. In Toronto, Canada, constructions with a floor area larger than 2000 m^2 must implement green roofs on 20−60% of the total surface. China, Hong Kong, and South Korea's governments encourage green roof practices for environmental sustainability and mitigation of the effects of climate change [13].

The successful green roof implementations in the USA and Europe, have triggered the global interest in green roof research. Since most research on green roof implementations have been conducted by northern European countries, it is important that recent research focuses on adapting green roofs to different climates and building characteristics as well. Finally, it is vital that further investigation focuses on more innovative, cost-effective designs of green roof models for meeting practical, large-scale benefits.

2.3 EXAMPLES OF MODERN GREEN ROOF SYSTEMS

Nowadays green roofs have evolved a lot in terms of design and effectiveness. There are multiple innovative and architecturally advanced designs around the world. Some of the most impressive green roofs are demonstrated below.

The California Academy of Sciences Living Roof – San Francisco, Calif., United States [21].

One of the most famous green roofs today can be found at the *California Academy of Sciences* (CAS) in San Francisco, California. On this green roof, there are weather stations that monitor wind, rain, and temperature changes. These weather stations provide valuable data to the building's automated systems and skylights. This data helps maintain a cool and comfortable environment in the interior piazza and ensures that natural light flows into the exhibits below.

Figure 5: The California Academy of Sciences Living Roof – San Francisco, Calif., United States [21].

According to the CAS website, the roof features seven hills bordered by solar panels, and it incorporates 50,000 porous vegetation trays made from tree sap and coconut husks. Approximately 1.7 million plants fill these trays, with their roots interlocking to create a unique sanctuary for birds, insects, people, and other creatures. Additionally, the Academy holds the distinction of being the world's first Double Platinum LEED-certified museum and the largest Double Platinum building globally.

ACROS Fukuoka Prefectural International Hall – Fukuoka City, Japan [21].

Renowned green architect *Emilio Ambasz* achieved a remarkable feat by translating an almost 100,000-square-meter park from the city center onto 15 stepped terraces of the ACROS Fukuoka Prefectural International Hall. *Ambasz's* design for ACROS Fukuoka introduces an ingenious approach to address a common urban dilemma: how to balance a developer's goal of maximizing a site's profitability with the community's demand for accessible green areas. The Fukuoka project ingeniously satisfies both requirements within a single structure, establishing an innovative agro-urban model.

Figure 6: ACROS Fukuoka Prefectural International Hall – Fukuoka City, Japan [21].

The Vancouver Convention Center – Vancouver, BC, Canada [21].

The West building of the *Vancouver Convention Centre* boasts a six-acre living roof, which holds the distinction of being both the largest in Canada and the largest non-industrial living roof in North America. This expansive green roof is adorned with over 400,000 native plants and grasses, strategically designed to function as an insulating layer, reducing heat gains during the summer and heat losses in the winter. On the underside of the roof, you'll find stunning Douglas fir slats, sourced locally. A distinctive aspect of this roof is the presence of four beehives, where European honeybees are kept. These bees play a crucial role in pollinating the plants on the living roof while also supplying honey for the kitchen.

Figure 7: The Vancouver Convention Center – Vancouver, BC, Canada [21].

The Nanyang Technological University – Singapore [21].

The standout feature of the *School of Art Design and Media* at the University is its striking green roof, which is inclined at nearly a 45-degree angle. This sunken, almond-shaped courtyard is created between the two main wings of the building and is elegantly mirrored by the high-performance, double-glazed glass curtain wall facades from the inside. The green roof serves a dual purpose as an attractive outdoor communal area and a means to maintain a lower ambient temperature, reducing daytime heat. Furthermore, the reflective pond in the central courtyard offers a refreshing visual oasis and contributes to cooling the central space.

Figure 8: The Nanyang Technological University – Singapore [21].

The grassy surface of the roof comprises a combination of two grass types, *Zoysia matrella* and *Ophiopogon*. Below the grass roof, there are four interconnected layers, including crushed volcanic rocks, pumice, washed sand (to facilitate grass rooting), and a moisture retention mat. To ensure the turfgrass remains lush and vibrant year-round, it is nourished by an automated sprinkler system that uses collected rainwater.

Chicago City Hall Green Roof - Chicago, Ill., United States [21].

City Hall in Chicago is home to the city's most renowned rooftop garden. Originally established in the year 2000, this rooftop garden project was conceived to test the advantages of green roofs and their impact on temperature and air quality. The garden is comprised of 20,000 plants encompassing over 150 different species, including shrubs, vines, and two trees. The selection of plants was based on their resilience in the roof's challenging conditions, which include sun exposure, wind, and aridness. Most of these plants are native prairie species from the Chicago region.

Figure 9: Chicago City Hall Green Roof - Chicago, Ill., United States [21].

The City Hall rooftop garden enhances air quality, conserves energy, reduces stormwater runoff, and contributes to mitigating the urban heat island effect. The plants in the garden reflect heat, offer shade, and aid in cooling the adjacent air through the process of evapotranspiration.

2.4 BENEFITS

Green roofs offer various environmental benefits, such as enhanced stormwater control, reduced building energy usage, diminished noise pollution, alleviated urban heat island effect, and the expansion of green areas within urban settings. The benefits of green roofs also include social benefits like the enhancement of conditions for urban wildlife, as well as the improvement of urban atmosphere and aesthetic.

2.4.1 Environmental and Social benefits

Green roofs can improve the visual appeal of an area and contribute positively to the local wildlife. They offer a respite from the prevalence of concrete structures by introducing pockets of greenery into urban environments. From an aesthetics perspective, one of the key purposes of a living green roof is to offer a visually engaging layer of vegetation with a variety of textures and seasonal colors, as opposed to a rock ballast or a dark-colored cement surface [20]. Numerous studies have shown that green roofs have a positive impact on urban residents by providing a visually appealing oasis [13].

Furthermore, green roofs can open possibilities for urban agriculture, specifically roof gardening, enabling the cultivation of various vegetables and contributing to the self-sufficiency of communities in food production [13].

Additionally, Green roofs in urban and suburban settings serve as a kind of green pathway, acting as steppingstones for wildlife to access nearby habitats. They can bridge the gaps between fragmented habitats, thereby enhancing urban biodiversity. In fact, researchers have documented the presence of as many as 30 different species of organisms on these green roofs. Among these species, *Isotoma viridis* and *Parisotoma notabilis* are particularly noteworthy, as they are considered cosmopolitan pioneers in urban soils [16].

2.4.2 Energy benefits

Green roofs serve two vital purposes for the buildings they are implemented on: decreasing surface temperatures and enhancing thermal comfort. They achieve this by enhancing a building's insulation, since green roofs' vegetation and substrate absorb less solar radiation, compared to conventional roofs. As a result, during the summer cooling effects are achieved and energy expenses are lowered [13]. Additionally, the planting medium and vegetation cover also contribute to shading the roof surface, which in turn reduces solar heat gain or loss and lowers the energy consumption required to heat and cool the building beneath [20]. Research conducted in Japan demonstrates that green roofs can lower surface temperatures by as much as 30°C to 60°C [13], which indicates that such structures can help save energy required for cooling buildings. *Marco A. Polo-Labarrios* et al. [19] developed a heat transfer transient model to compare a conventional building with one that had a green roof installed. The results proved that green roofs could alleviate variations in indoor temperatures within structures, effectively decreasing these fluctuations by as much as 14 degrees Kelvin. Another analysis of energy performance conducted on a nursery school building with a green roof system in Athens, Greece by *M. Santamouris* et al. [8] the results showed that the incorporation of a green roof system made a substantial contribution to enhancing the building's energy efficiency. The cooling demands of the building during the summer season decreased, which lead to a significant reduction in the use of conventional air conditioning. On the other hand, the influence of green roof systems on heating requirements during the winter months is generally considered to be negligible.

Numerous research investigations have explored the potential role of green roofs in promoting urban sustainability by mitigating the UHI effect. The transpiration process of the vegetation creates an evaporative cooling effect, which can locally reduce air temperatures below the ambient level [20]. More specifically, green roofs help lower surrounding temperatures, during the daytime by providing shade through the plants and by allowing them to release moisture through tiny openings in their leaves, called stomata. This cooling effect occurs due to the ability of the plants to absorb and store heat, which helps cool the surrounding air. As a result, the highest daily temperatures on green roofs are reduced, as well as the daily temperature fluctuations. Research conducted in the United States showed that green roofs can lower peak temperatures by anywhere from 0.5°C to 3.5°C, and in addition to the cooling effect, they can increase the albedo from 0.05 to 0.61 [15].

Studies have revealed that green roofs have the most significant impact in regions characterized by hot and dry climates. In Singapore, *Qin* et al. conducted measurements of surface temperatures on both green and conventional bare roofs. When they compared the outcomes, the green roof demonstrated promising results in effectively reducing surface temperatures compared to the bare roof [13]. However, green roofs are effective in lowering surface temperatures in both cold and hot regions. *Sun* et al. conducted a study on green roofs at two distinct locations: *Tsinghua University* in China and *Princeton University* in the United

States, with the goal of analyzing changes in surface temperatures. Interestingly, the findings indicated that green roofs successfully reduced surface temperatures and heat loss at both locations [13].

2.4.3 Air quality

Green roofs possess the ability, depending on the type of vegetation, to trap harmful fine dust particles from the air, offering a potential solution for enhancing human comfort in densely developed urban regions. Urban areas often suffer from elevated levels of fine dust particles in the air, which degrade the quality of the urban environment and create discomfort. A study from Zhengzhou, China indicates that tree species are responsible for capturing 87.0% of the dust in the air, while shrubs for 11.3%, and finally lawns for 1.7% [13]. Green roofs contribute to mitigating air pollution through two distinct mechanisms. Firstly, plants on green roofs capture small airborne pollutants through their stomata. Secondly, green roofs reduce surface temperatures, which, in turn, can reduce the need for burning fossil fuels to meet energy demands, further aiding in air quality improvement.

2.4.4 Water retention

In recent years, floods have had a profound impact on our planet. They disrupt ecosystems, leading to habitat destruction and threatening biodiversity. Green roofs represent an excellent approach to managing stormwater effectively within urban settings due to their unique capacity for water retention. They utilize natural processes to gather, purify, and enhance the quality of runoff water, in contrast to traditional infrastructure that merely captures and channels water into the sewer system [17]. This significant advantage of living green roofs lies in their ability to slow down and retain stormwater runoff through a porous, vegetated surface. Consequently, they contribute to a decreased risk of sudden urban flooding, help conserve water resources, and eliminate the need for expensive and environmentally taxing stormwater management systems. The capacity of stormwater, vegetation and soil can capture and retain relies on factors such as the type and coverage of vegetation, the terrain's slope, and the composition of the underlying soil. A denser vegetation cover, a gentler slope, and more permeable soil enhance the system's capability to intercept and retain stormwater before it reaches the ground, as well as detain it after it lands [20]. Lastly, it is worth noting that recent research shows that green roofs can potentially upgrade the quality of the runoff water. Specifically, the findings indicate that the proportion of heavy metals in urban runoff originating from hard surfaces is notably greater compared to runoff from surfaces covered by green roofs [13].

2.4.5 Noise reduction

Another important benefit of green roofs is their ability to decrease noise pollution. Compared to roofs with no vegetation, green roofs can significantly reduce noise by absorbing sound waves, thereby lowering the overall noise levels. *Yang* et al. conducted field experiments on green roofs to evaluate their effectiveness in reducing urban noise. The results demonstrated that the vegetation on green roofs has a high absorption coefficient, which greatly contributes to noise reduction [13]. Another research conducted by *Connelly* and *Hodgson* proved that green roofs were able to decrease noise frequency by 10-20 dB [13].

2.4.6 Economic benefits

From an economic standpoint, implementing living green roofs can fulfill the stormwater management criteria set by local governments. This, in turn, leads to a reduction in expenses when compared to the conventional methods used to channel stormwater from rooftop drains to its final destination. This cost savings not only benefits property owners during construction but also alleviates the substantial financial burden on municipalities responsible for stormwater management infrastructure and operations. As a result, many municipalities now encourage more elaborate and intricate green roof designs in terms of their size, complexity, and associated expenses, exceeding the minimum requirements for supporting a functional living green roof [20]. It's worth noting that the necessity to coordinate various professional disciplines throughout the design, documentation, and construction stages carries cost implications that must be carefully weighed against the advantages of the end use.

2.5 CLASSIFICATION OF GREEN ROOFS

Green roofs can be classified into three categories, those being *extensive*, *semi-intensive*, and *intensive* green roofs.

Extensive green roofs have a thin layer of soil (less than 15 cm deep), which results in low initial costs and relatively small weight added to the structure. However, they can only accommodate specific types of vegetation, like grasses, moss, and some succulents. Due to their vegetation type, extensive green roofs are resistant to cold weather and strong wind. Additionally, extensive green roofs demand low energy and water supply as well as minimal maintenance and are often chosen when there is a need to avoid additional structural support [12].

Figure 10: Extensive green roof [37].

On the contrary, *intensive* green roofs have a thick layer of soil (ranging from 20 to 200 cm deep) and support a wide variety of plants, including shrubs and small trees. They require high maintenance and involve significant initial costs. This maintenance includes tasks such as fertilizing, weeding, and watering. Furthermore, intensive green roofs add a substantial amount of weight to the building and so a static investigation of the structure must be conducted [12].

Figure 11: intensive green roof [37].

Semi-intensive green roofs fall in between, with a moderately thick substrate layer that can support small herbaceous plants, ground covers, grasses, and small shrubs. These roofs require regular maintenance and come with higher capital costs compared to extensive ones [12].

Figure 12: Semi-intensive green roof [37].

In practice, extensive green roofs are the most widely used globally because they align with building weight restrictions, cost considerations, and the desire for lower maintenance.

2.6 COMPONENTS AND MATERIALS

Unlike a conventional rooftop, green roofs are structurally more complicated and require the installation of various layers (figure 13). Each layer consists of different materials and performs unique functions that contribute to the effectiveness of the green roof system. This chapter cites and analyzes the layers of a green roof structure.

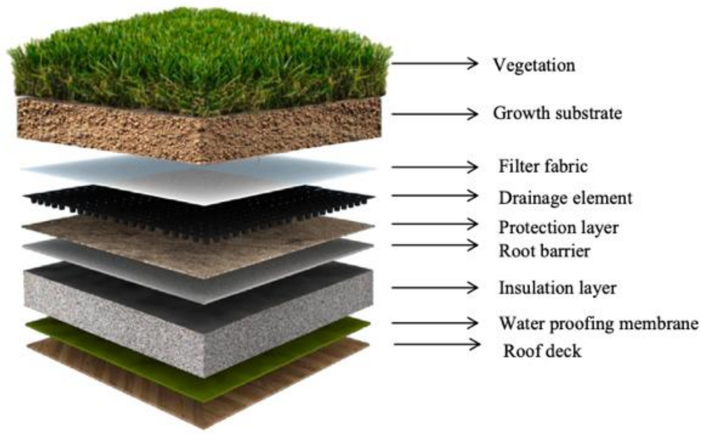

Figure 13: The structure of a green roof [21].

2.6.1 Vegetation

The topmost layer of a green roof is comprised of plants, which play a crucial role in bringing vitality to the entire green roof system. In short, the effectiveness of a green roof revolves around the well-being of these plants. The choice of vegetation suitable for a green roof depends on the roof's construction style. In extensive green roofs, where the substrate layer is thin, the primary vegetation options are herbs, succulents, or grasses. However, as you increase the substrate thickness and invest in support systems like irrigation and maintenance, such as in semi-intensive to intensive green roof designs, you can expand your plant selection to include shrubs and even trees [13].

When it comes to herbaceous plants, the options typically involve either grafting or seeding directly into the soil bed. On the other hand, for rooted grafts, planting is carried out in specifically designated regions within the soil bed. The ideal balance between herbaceous and evergreen plants contributes to the creation of diverse gardens that offer both aesthetic and environmental benefits. Depending on the overall area covered, green roofs encompass a variety of elements, including trees, shrubs, flowerbeds, and other formations like ponds [9].

In rooftop settings, water availability is consistently a limiting factor, with significant fluctuations between rain events. When planning green roof projects, it's crucial to consider essential climate factors like rainfall patterns, drought occurrences, frost periods, and prevailing winds. Additionally, specific factors, such as plant selection, assessment of sunny and shaded areas, consideration of emissions from building vents and other structures, and examination of wind patterns unique to the location, must be carefully considered right from the project's outset [14]. Furthermore, it's essential to factor in the specific characteristics and requirements of the chosen plant species. These include aspects like species competition (invasive species), sensitivity to air pollutants, plants with invasive root systems, susceptibility to light reflections and heat accumulation, and stability against strong winds, etc. [14].

Choosing the appropriate plant species for green roofs hinges on factors such as desired plant height, flowering season, and the specific soil requirements of these plants. Table 1 provides information on various plant species suitable for green roof systems, detailing their flowering seasons, preferred soil types, and ultimate heights. Meanwhile, Table 2 highlights plant species suitable for Mediterranean climates [9].

Table 1: Plant species suitable for green roof, their flowering seasons, the desired soil type and their final height [9].

Plant species suitable for green roof, their flowering seasons, the desired soil type and their final height			
Plant species	Flowering season	Soil type	Final height in cm
Lavendula vera	Summer	Well drained	40-60
Sedium acre	June-July	Well drained	2-10
Erica spp.	All the seasons	Acid	40-50
Dianthus deltoides	June-September	Well drained	15-45
Armeria maritima	April-May	All the types	10-20
Bellis perennis	March-April	Well drained	7-15
Campanula rotundifolia	July-September	Well drained	15-40
Saponaria officinalis	June-September	Well drained	30-60
Linaria vulgaris	July-October	All the types	30-80

Primula vulgaris	March-June	All the types	8-15

Table 2: Plant species suitable for Mediterranean [9].

Plant species suitable for Mediterranean			
Plant species	Flowering season	Soil type	Final height in cm
Nerium oleander	Summer-Autumn	All types	80-90
Pyracantha sp.	Spring	Well drained	60-70
Myoporum sp.	Spring	Acid	80-90
Cotoneaster franchetti	Spring	Well drained	50-70
Hibiscus syriacus	Summer-Autumn	Well drained	40-60
Cassia corymbose	Summer-Autumn	Well drained	40-60
Spiraea thumbergii	Spring	All types	40-50
Ryracantha sp.	Summer-Autumn	All types	80-90
Myoporum sp.	Spring	Well drained	60-70
Cotoneaster franchetti	Spring	Acid	80-90

Maintaining the vegetation on green roofs is a vital process. Pruning should be performed on larger plants to secure them against strong winds, and regular inspection and unclogging of drainage systems are essential to prevent undesired situations arising from inefficient drainage [9].

2.6.2 Substrate layer

The growing medium plays a central role in nurturing vegetation on green roofs. It serves not only as a physical support but also as a vital source of water and nutrients, essential for the plants' development [14].

Restrictions based on building load capacity impose constraints on the depth and weight of the substrate. The growth medium should contain only minimal nutrients, to prevent weed growth and avoid the generation of nutrient-rich runoff. This requirement leads to the use of nutrient-deficient inorganic recycled materials as the primary components of green roof substrates [13]. As stated by *Vijayaraghavan* in 2016 [13], the ideal characteristics for a green roof substrate should include high stability, strong anchorage for plants, versatility to support a wide range of plant types, minimal organic content, low bulk density, excellent water retention, high *air-filled porosity* (AFP), efficient water drainage, high *water holding capacity* (WHC), and minimal nutrient leaching [14]. A higher WHC not only reduces peak runoff flow but also provides crucial support to plants during dry spells. One way to enhance WHC is by increasing the volume and depth of the substrate. Additionally, some researchers suggest incorporating additives to optimize the growing media's water holding capacity. Additionally, AFP promotes consistent water flow during rainfall events and prevents water from seeping out of the green roof [13].

However, it's a challenging task to find or create a green roof substrate that encompasses all these desirable qualities simultaneously. In some cases, adjustments may be necessary, as enhancing one characteristic could potentially compromise another. For example, reducing bulk density by using lightweight minerals might affect substrate stability and plant anchorage. Similarly, altering particle size and increasing organic matter to improve water retention may impact air space and water drainage. Nonetheless, a well-designed substrate should aim to preserve the primary advantages offered by a green roof [14]. The common approach is to combine different ingredients that contribute the essential and desired properties to the substrate. Typically, these ingredients are categorized into two main fractions: the inorganic fraction and the organic fraction [13].

Regarding the inorganic fraction, there is a wide array of materials that can be employed, including scoria, ash, pumice, zeolite, vermiculite, sand, coir, pine bark, and even recycled materials like crushed bricks, porcelain, and tiles, among others [14].

Organic components in the substrate, such as mulch and peat, are recommended to provide essential nutrients for green roofs [13]. However, it is recommended to keep organic matter content to a minimum. While organic matter can enhance plant growth and moisture retention in the substrate, it often has a relatively brief lifespan. Over time, it tends to break down, compact, and can even become water-resistant, making it challenging to rehydrate if it dries out. Guidelines typically recommend keeping organic matter below 6% for extensive green roofs [14].

As previously mentioned, the growth medium for green roofs needs to have a low bulk density because a high bulk density could potentially damage the structure. This is especially critical in older buildings with weight restrictions that cannot support the additional load from heavy substrates. Consequently, a constant effort must be made to minimize the weight of green roofs. Some researchers have even proposed using 80% inorganic materials in the green roof growing medium to further reduce weight [13].

The depth of the green roof substrate plays a crucial role in determining the types of plant species that can be accommodated and defines the various categories of green roofs, namely extensive, semi-intensive, and intensive. Typically, the substrate depth remains uniform across the entire green roof surface, which is often chosen to ensure consistency in the selection of plant species, especially in extensive green roofs. However, in a more imaginative and nature-inspired approach to green roofs, introducing diversity in substrate depth becomes a vital aspect. According to *Gedge* et al. (2013) [13], one common method to achieve this diversity is by creating areas with shallower substrate (hollows) in contrast to areas with elevated mounds of substrate. This not only results in variation in substrate depth but can also lead to differences in exposure, with mounds being more susceptible to wind and drying out as they rise above the main roof level. Additionally, it influences hydrology, allowing water to drain from the mounded areas into the hollows. This approach is anticipated to enhance biodiversity by supporting a wider range of invertebrates and plant species [14].

It is worth mentioning that the primary difficulty lies in crafting substrates suitable for extensive green roofs (and to some extent, semi-intensive roofs). This challenge arises because intensive green roofs do not face the same constraints and limitations [14].

2.6.3 Filter layer

The primary role of a filter layer is to create a barrier between the growth substrate and the drainage layer. This barrier serves to prevent the infiltration of small particles, such as plant debris and fine soil, into the drainage layer below, thus preventing clogs. In typical green roof construction, geotextile fabrics are commonly employed. These filter fabrics are expected to possess substantial tensile strength to support the weight above and feature small pores to facilitate water flow in the normal direction while impeding the movement of soil particles into the drainage layer. Additionally, the filter fabric serves as a membrane to deter the growth of soft and shallow-rooted plants [12].

2.6.4 Drainage layer

The drainage layer plays a pivotal role in the functionality of green roofs by facilitating the efficient removal of excess water from the substrate. This serves a dual purpose: firstly, it reduces the burden on the building, diminishing the risk of structural collapse. Secondly, it acts as a protective barrier for the waterproof membrane while enhancing the overall energy efficiency of the building. Two primary categories of drainage layers are commonly employed [13]:

- Drainage Modular Panels: These panels are typically constructed from materials such as polyethylene or polystyrene and feature perforations that allow for the storage of water while facilitating the drainage process.

- Drainage Granular Materials: These materials have substantial pore spaces to accommodate a greater volume of water. Examples include *lightweight expanded clay aggregates* (LECA), expanded shale, crushed brick, coarse gravel, and stone chips.

2.6.5 Root barrier

In the realm of green roofs, the necessity of a root barrier varies depending on whether it's an intensive or extensive type. For intensive green roofs, a root barrier is an essential component, while for extensive ones, it remains an optional consideration. The primary objective behind incorporating a root barrier is to safeguard the structural integrity of the roof against the potential intrusion of plant roots from the upper layers of the green roof. A range of materials can be used as root barriers, including options like rigid plastic sheets and, in some cases, metal sheets, often made of copper [12].

2.6.6 Insulation layer

The inclusion of an insulation layer in roofing systems is a discretionary choice. Its primary function is to prevent the absorption of heat during winter or the loss of cool air during summer from the water stored within the green roof system. In retrofitting projects where green roofs are added to existing roofs, there is typically a greater need for additional insulation. The decision to include insulation depends on the specific design and type of roof in question. Nonetheless, when utilized, it is positioned above the waterproofing layer, serving the dual purpose of safeguarding the membrane against condensation and physical damage [13].

2.6.7 Waterproofing layer

Even if waterproofing is not considered a traditional component of a green roof, it is an essential prerequisite during the installation phase to prevent any potential leaks. Due to the persistent moisture content in the roof caused by the presence of wet soil and a drainage layer, the risk of leaks is ever-present. Moreover, in the event of a leak in an operational green roof, the entire layer system must be dismantled to locate and address the issue. Therefore, the application of a waterproof layer is strongly recommended. There are various options available for waterproofing, including liquid-applied membranes, single-ply sheet membranes, modified-bitumen sheets, and thermoplastic membranes. The choice of the waterproofing method depends on the type of green roof, cost considerations, availability of materials, and the expected lifespan of the waterproofing solution [12].

2.7 FACTORS AFFECTING THERMAL PERFORMANCE

Green roofs typically dissipate heat through three primary mechanisms: evapotranspiration, heat loss via longwave radiation, and photosynthesis. These processes contribute to heat loss on green roofs, with evaporation accounting for 51.5%, longwave radiation accounting for 40%, and photosynthesis accounting for 8.5% of the total heat loss. It's worth noting that in most cases, only a minimal amount of heat (0.5%) is transferred from the roof to the building [25]. The most important parameters influencing the thermal performance of a green roof are demonstrated in the following paragraphs.

2.7.1 Thermal insulation

One crucial factor affecting the cooling effect and thermal performance of green roofs is thermal insulation. The level of thermal insulation in green roofs, mainly determined by the depth of the growth medium, stands out as a critical parameter that significantly influences their cooling capacity. In another investigation carried out in Southern Italy [25], the thermal effectiveness of two green roofs, each featuring distinct substrate depths, was examined. The study findings indicated that green roofs with substrate depths of 20 cm and 10 cm demonstrated significant reductions in heat transfer, with reductions of 96% and 59%, respectively, compared to a typical roof. It was highlighted that the thermal capacity of the substrate is as crucial as its thickness in enhancing the cooling capacity of green roofs.

2.7.2 Evapotranspiration

The second crucial factor influencing the cooling effect of green roofs is the cooling process facilitated by evapotranspiration from plants. Evapotranspiration consists of two components: evaporation and transpiration. Evaporation involves the transfer of moisture and water from the soil into the air, while transpiration is the release of water vapor from plant parts such as leaves and the outer surface of the canopy. Leaves additionally contribute to cooling by dissipating heat through the emission of long-wavelength radiation (within the 400–700 nm range). Both latent heat (associated with evaporation) and sensible heat (associated with convection) play a role in dissipating heat from the green roof. It's important to mention that the extent of heat loss through evapotranspiration varies significantly based on the specific green roof type. For instance, intensive green roofs, characterized by dense and thick layers of vegetation and soil, tend to exhibit a high rate of evapotranspiration [25].

2.7.3 Shading effect and heat flux

The third and final critical factor impacting the thermal performance of green roofs is the shade provided by the vegetation. The *Leaf Area Index* (LAI) is considered the most suitable parameter for quantifying the shading effect, which plays a role in cooling through evapotranspiration and the provision of shade against solar radiation. A study conducted by *Saadatian* [25], indicated that the highest daily surface temperature, initially at 42 °C, can be reduced to 36 °C because of the vegetative cover on green roofs.

The introduction of green roofs also leads to a reduction in heat flux. In an Italian study [25], the heat flux levels of wet green roofs, dry green roofs, and traditional bare roofs were compared. The results demonstrated that, because of evapotranspiration, heat loss from wet green roofs was twice as high as that from dry green roofs. Conversely, the heat transfer into buildings was found to be 60% higher in conventional bare roofs compared to dry roofs.

2.8 LIMITATIONS AND CONSTRAINS

Numerous factors impede the expansion of green roofs in most counties. Before implementing such a structure there are various factors that must be taken into consideration. The most important constrains and limitations will be analyzed on the following paragraphs.

2.8.1 Cost

The primary obstacle revolves around the expense associated with green roof implementation. It is commonly perceived that green roofs represent a prolonged financial commitment with minimal immediate gains. To elaborate, setting up a green roof necessitates a substantial upfront investment, with costs varying depending on the type of green roof, its location, labor requirements, and necessary equipment. Additionally, the total number adds up even more when considering maintenance and final disposal costs. Limited research has been conducted to assess the expenses associated with green roof systems in urban settings. Consequently, determining the return on this investment is uncertain. *Niu* et al. [12] analyzed the cost of a 1795 m^2 roof in Washington DC. They found that the total cost of the construction of the green roof was 27% higher than that of the conventional roof. Although, after 40 years, when conducting the same analysis, while contemplating the benefits from the installation of the green roof, it was demonstrated that the *present net value* (PNV) of the green roof was 25% lower than the conventional roof. However, that was not the case when *Lee* [12] conducted a life cycle analysis of a green roof installed in a rooftop of a building in Oregon. While considering all the benefits and energy savings for a time period of 60 years, the results demonstrated that the green roof was 7% more expensive that the conventional roof. Variations in outcomes of this nature are anticipated due to the study's execution across diverse geographical regions. Furthermore, many of these studies overlooked certain elements in their cost-benefit analyses whereas, quantifying the enhancements in air quality and the mitigation of the UHI effect pose substantial complexities. Additional advantages offered by green roofs, such as aesthetic improvements, ecological conservation, and noise reduction, are subjective and do not directly translate into tangible savings for property owners. Consequently, justifying the cost of green roofs becomes a daunting challenge. Nonetheless, green roofs offer many benefits that could potentially balance out their high cost and this is a statement that deserves further investigation.

2.8.2 Maintenance

Maintaining a green roof is another complex challenge and research in this area remains quite limited. Green roofs require consistent watering, particularly in dry climates, occasional fertilization, and demand regular maintenance checks. A solution that reduces the need for frequent irrigation is the implementation of succulent species of plants. However, this limited variety of plant species interferes with the aesthetic appeal of green roofs. To be more specific, the extent and frequency of the maintenance needed depends on the type of the green roof. For instance, extensive green roofs typically require relatively simpler tasks like drainage inspection, and weed removal, while intensive green roofs demand more comprehensive and detailed maintenance procedures. Regardless of the green roof type, dealing with weed removal is a challenging and time-consuming maintenance task [12].

2.8.3 Sustainability

Most green roof elements, apart from the substrate and vegetation layers, are typically crafted from polymer materials. Due to weight restrictions and the harsh conditions found on rooftops, the use of resilient polymeric materials seems necessary for component construction. However, the total energy expended in producing these elements and the resultant environmental pollution raise a significant question: How environmentally friendly are green roofs? *Bianchini* and *Hewage* [12] conducted research on the materials used for each layer of a green roof. The data collected demonstrate that drainage and filter layers in green roofs are, generally, manufactured using 40% of recycled polypropylene, while the water retention layer utilizes 100% recycled polymeric fibers. However, the authors promptly noted that any pollution generated during the production of these polymers could potentially be offset by the long-term environmental benefits of green roofs. Hence, exploring alternative materials to replace the current reliance on polymers is necessary to enhance the overall sustainability of green roof systems.

2.8.4 Research on materials

In a comprehensive examination of green roof research publications, *Blank* et al. [12] discovered that only 31 countries are involved in publications regarding research on green roof construction, with the United States and the European Union accounting for 66% of the research contributions. Due to this dearth of research in developing and underdeveloped countries, these regions lack awareness regarding suitable green roof components for their specific geographic locations. Thus, the importation of green roof components often results in high installation costs as well as the potential for failure due to compatibility issues.

2.8.5 Rooftop leakage

While there have been a limited number of reported building collapses, it is important before the installation of a green roof system, that thorough evaluations are conducted by experts. Additionally, the careful choice of suitable components, and the scrutiny of their characteristics can effectively prevent structural damage. Many studies have shown that a green roof enhances the longevity of the roof by shielding the roof's waterproof membrane from UV radiation, extreme heat, and cold, and potential mechanical damage. According to *Kosareo* and *Ries* [12], extensive green roofs can extend the roof system's lifespan up to 25 years, nearly doubling that of a traditional roof.

2.8.6 Ultimate disposal

Given the quantity of materials required for constructing green roofs, the eventual disposal of these spent green roof components raises significant concerns related to labor, expenses, and environmental repercussions. Even though numerous studies have applied methods like *Benefit-Cost Analysis* (BCA) or life cycle cost assessments to gauge the overall cost of green roofs, none of these assessments have factored in the disposal expenses associated with such structures. In essence, the disposal phase of a green roof involves the disassembly of all its components and their transportation to landfills. Some components, such as the growth medium, can potentially find reuse in other applications, while the vegetation can be repurposed as compost or disposed of as biodegradable waste [12]. However, the presence of plastic materials, particularly in the filter and drainage layers, poses a challenge. *Peri* et al. [12] conducted a case study to assess the disposal costs of various components commonly utilized in green roofs supplied by an Italian green roof manufacturer. Their findings revealed that disposal costs accounted for just 4.6% of the total expenses, with the initial capital cost comprising 36.1% and maintenance expenses constituting 59.3% of the overall costs.

3 GREEN ROOFS AND SUSTAINABILITY

During the last ten years, green roofs have gathered significant worldwide interest because of their numerous social and environmental advantages. Currently, there is a growing global effort to conduct research on assessing the environmental impacts of green roofs.

Fabricio Bianchini and *Kasun Hawage* (2012) [26] conducted a study on the ecological advantages of green roofs. They compared the emissions of pollutants like NO_2, SO_2, O_3, and PM_{10} during the production of green roof materials (such as polymers) with their capacity to reduce pollution. The results showed that the air pollution generated during polymer production can be offset by green roofs within a span of 13 to 32 years.

On a different study *Sanaz Bozorg Chenani*, et al. (2015) [27] identified the potential ecological impacts associated with the various layers of two entire lightweight green roof systems. The findings indicated that the components in the water retention, drainage, and substrate layers had the most significant adverse environmental effects. Concludingly, it was advised to avoid using Rockwool, virgin HIPS, and expanded clay, as long as these materials do not compromise the required performance. Additionally, it was recommended to opt for simpler roof systems as well as recycled and locally sourced materials, since they are more environmentally friendly compared to virgin materials that require transportation over long distances.

Lisa Kosareo and *Robert Ries* (2007) [27] compared the conducted a comparative environmental life cycle assessment between a conventional and an extensive and intensive green roof in Pittsburgh, PA, USA. They also concluded that selecting green roofs for building construction is an ecologically sound decision because they lead to both a decrease in energy consumption and extend the lifespan of the roofing membrane.

Furthermore, in a study by *Saiz* et, al. (2006) [28], they performed a comparative analysis of the life cycle energy usage for three roof types installed on an eight-story apartment building in Madrid, Spain. Between a conventional flat grey gravel roof, a white-painted roof, and a green roof it was revealed that the green roof contributed to a more than 1% decrease in annual energy consumption and a 6% reduction in the building's cooling requirements during the summer.

3.1.1 Life cycle assessment

Life Cycle Assessment (LCA) is a valuable scientific methodology for assessing the environmental effects across the entire lifespan of a product. The *LCA* process encompasses various stages, including material extraction, transportation, operational use, maintenance, and eventual disposal. Numerous research findings have demonstrated that incorporating *LCA* is an effective approach for realizing the environmental and energy performance of materials and products over their complete lifecycle [17].

LCA offers many benefits. First and foremost, it evaluates the impacts on human and ecological well-being due to material usage and environmental releases, spanning from the local community to a global scale [38]. The results of a LCA study, along with cost and performance data, can help enlighten the decision-making process. Since, LCA follows a "cradle-to-grave" approach, it points out chances to enhance the environmental sustainability of products at different stages of their life cycle [39], as well as enables the evaluation of the pros and cons of various production methods [40]. Another benefit of LCA that makes it stand out from other methods is the fact that it enables a decision-maker to examine an entire product system, preventing potential sub-optimization that could occur if only a single process were the focus of the study. For instance, between two products or processes, it might seem that *product A* is more environmentally friendly because it generates less solid waste compared to product B. However, the LCA results may reveal that *product A* actually results in greater “cradle-to-grave” environmental effects, such as increased chemical emissions during the manufacturing phase. Consequently, *product B*, despite producing more solid waste, appears to cause less overall environmental impact due to its lower chemical emissions [38]. Additionally, LCA has intermittently served businesses for marketing endeavors. It stands as a critical tool for substantiating advertising claims in competition with rival products, demanding full transparency in how results are assessed and presented [40].

Nowadays, *LCA* has been used in evaluating the environmental impact of various green infrastructure practices, such as green roofs, over their entire lifespan. Utilizing *LCA* can offer valuable insights for selecting more cost-efficient and environmentally friendly materials for constructing green roofs. Nevertheless, a comprehensive research effort is necessary to thoroughly assess green roofs, encompassing both environmental and cost considerations, to achieve sustainable design. This integrated approach is crucial for informed decision-making when incorporating green roofs, including the choice of materials for different layers, in building projects with environmentally conscious practices [31].

4 CONCLUSIONS

The world is currently undergoing significant transformations, with the increasing urbanization and the impact of climate change being from the most profound. Nowadays, over half of the global population resides in urban areas, and this proportion is expected to grow in the coming years. Urban areas face elevated temperatures in comparison to their surrounding natural environments, due to various factors that shape the urban climate and give rise to what we call "*Urban Heat Islands*".

The UHI effect has many negative effects on both the environment and human health. Thus, it is of paramount importance to tackle the UHI phenomenon and implement successful strategies to mitigate its effects. The most effective solution involves the expansion of green areas. Therefore, increasing greenery within cities and widely adopting green infrastructure emerge as the most preferred approach for cooling urban environments.

The concept of green roofs has existed since ancient times. Nowadays, there has been a notable rise in the prevalence of green roofs in cities worldwide. These structures represent one of several technologies aimed at fostering environmentally sustainable building practices and enhancing the visual appeal of urban landscapes. *Green roofs* provide a great range of environmental advantages, including among others decreased energy consumption in buildings, reduced noise pollution, mitigation of the urban heat island effect, and the expansion of greenery and biodiversity within city environments. While existing research has predominantly emphasized the overall benefits of these roofs, there is relatively limited consideration given to the environmental repercussions of such structures. Thus, the environmental burden of green roofs should be further reviewed and investigated. The *LCA* of such structures is a very good tool to examine and analyze the sustainability of green roof structures in order to finally answer the question "How 'green' are the green roofs?".

BIBLIOGRAPHY

1. Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. Journal of environmental management, 197, 522-538. https://doi.org/10.1016/j.jenvman.2017.03.095
2. Solecki, W. D., Rosenzweig, C., Parshall, L., Pope, G., Clark, M., Cox, J., & Wiencke, M. (2005). Mitigation of the heat island effect in urban New Jersey. Global Environmental Change Part B: Environmental Hazards, 6(1), 39-49. https://doi.org/10.1016/j.hazards.2004.12.002
3. Santamouris, M., Ding, L., & Osmond, P. (2019). Urban heat island mitigation. Decarbonising the Built Environment: Charting the Transition, 337-355. https://doi.org/10.1007/978-981-13-7940-6_18
4. Kim, S. W., & Brown, R. D. (2021). Urban heat island (UHI) variations within a city boundary: A systematic literature review. Renewable and Sustainable Energy Reviews, 148, 111256. https://doi.org/10.1016/j.rser.2021.111256
5. Heaviside, C., Macintyre, H., & Vardoulakis, S. (2017). The urban heat island: implications for health in a changing environment. Current environmental health reports, 4, 296-305. https://doi.org/10.1007/s40572-017-0150-3
6. Priyadarsini, R. (2009). Urban heat island and its impact on building energy consumption. Advances in building energy research, 3(1), 261-270. https://doi.org/10.3763/aber.2009.0310
7. Yu-Peng, Y. E. H. (2010). Green Wall-The Creative Solution in Response to the Urban Heat Island Effect. National Chung-Hsing University.
8. Santamouris, M., Pavlou, C., Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A., & Patargias, P. (2007). Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. Energy, 32(9), 1781-1788. https://doi.org/10.1016/j.energy.2006.11.011
9. Spala, A., Bagiorgas, H. S., Assimakopoulos, M. N., Kalavrouziotis, J., Matthopoulos, D., & Mihalakakou, G. (2008). On the green roof system. Selection, state of the art and energy potential investigation of a system installed in an office building in Athens, Greece. Renewable Energy, 33(1), 173-177. https://doi.org/10.1016/j.renene.2007.03.022

10. Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., & Mihalakakou, G. (2001). Analysis of the green roof thermal properties and investigation of its energy performance. Energy and buildings, 33(7), 719-729. https://doi.org/10.1016/S0378-7788(01)00062-7

11. Santamouris, M. (2014). Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar energy, 103, 682-703. https://doi.org/10.1016/j.solener.2012.07.003

12. Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. Renewable and sustainable energy reviews, 57, 740-752. https://doi.org/10.1016/j.rser.2015.12.119

13. Shafique, M., Kim, R., & Rafiq, M. (2018). Green roof benefits, opportunities and challenges–A review. Renewable and Sustainable Energy Reviews, 90, 757-773. https://doi.org/10.1016/j.rser.2018.04.006

14. Pérez, G., & Coma, J. (2018). Green roofs classifications, plant species, substrates. In Nature based strategies for urban and building sustainability (pp. 65-74). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-812150-4.00006-9

15. Santamouris, M. (2014). Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar energy, 103, 682-703. https://doi.org/10.1016/j.solener.2012.07.003

16. Li, W. C., & Yeung, K. K. A. (2014). A comprehensive study of green roof performance from environmental perspective. International Journal of Sustainable Built Environment, 3(1), 127-134. https://doi.org/10.1016/j.ijsbe.2014.05.001

17. Shafique, M., Azam, A., Rafiq, M., Ateeq, M., & Luo, X. (2020). An overview of life cycle assessment of green roofs. Journal of Cleaner Production, 250, 119471. https://doi.org/10.1016/j.jclepro.2019.119471

18. Scolaro, T. P., & Ghisi, E. (2022). Life cycle assessment of green roofs: A literature review of layers materials and purposes. Science of The Total Environment, 829, 154650. https://doi.org/10.1016/j.scitotenv.2022.154650

19. Polo-Labarrios, M. A., Quezada-García, S., Sánchez-Mora, H., Escobedo-Izquierdo, M. A., & Espinosa-Paredes, G. (2020). Comparison of thermal performance between green roofs

and conventional roofs. Case Studies in Thermal Engineering, 21, 100697. https://doi.org/10.1016/j.csite.2020.100697

20. Weiler, S., & Scholz-Barth, K. (2009). Green roof systems: a guide to the planning, design, and construction of landscapes over structure. John Wiley & Sons.
21. https://www.americanforests.org/article/impressive-green-roofs-around-the-world/
22. Aleksandrowicz, O., Vuckovic, M., Kiesel, K., & Mahdavi, A. (2017). Current trends in urban heat island mitigation research: Observations based on a comprehensive research repository. Urban Climate, 21, 1-26. https://doi.org/10.1016/j.uclim.2017.04.002
23. Nuruzzaman, M. (2015). Urban heat island: causes, effects and mitigation measures-a review. International Journal of Environmental Monitoring and Analysis, 3(2), 67-73. http://dx.doi.org/10.11648/j.ijema.20150302.15
24. Yamamoto, Y. (2006). Measures to mitigate urban heat islands. NISTEP Science & Technology Foresight Center. Retrieved by: http://www.5dstudios.com/clients/gcca/wp-content/uploads/2012/04/Measures-to-Mitigate-UHI-Yamamoto.pdf
25. Jamei, E., Chau, H. W., Seyedmahmoudian, M., & Stojcevski, A. (2021). Review on the cooling potential of green roofs in different climates. Science of the Total Environment, 791, 148407. https://doi.org/10.1016/j.scitotenv.2021.148407
26. Bianchini, F., & Hewage, K. (2012). How “green” are the green roofs? Lifecycle analysis of green roof materials. Building and environment, 48, 57-65. https://doi.org/10.1016/j.buildenv.2011.08.019
27. Chenani, S. B., Lehvävirta, S., & Häkkinen, T. (2015). Life cycle assessment of layers of green roofs. Journal of Cleaner Production, 90, 153-162. https://doi.org/10.1016/j.jclepro.2014.11.070
28. Kosareo, L., & Ries, R. (2007). Comparative environmental life cycle assessment of green roofs. Building and environment, 42(7), 2606-2613. https://doi.org/10.1016/j.buildenv.2006.06.019
29. Saiz, S., Kennedy, C., Bass, B., & Pressnail, K. (2006). Comparative life cycle assessment of standard and green roofs. Environmental science & technology, 40(13), 4312-4316. https://doi.org/10.1021/es0517522

30. Shafique, M., & Kim, R. (2017). Retrofitting the low impact development practices into developed urban areas including barriers and potential solution. Open Geosciences, 9(1), 240-254. https://doi.org/10.1515/geo-2017-0020

31. Zuo, J., Pullen, S., Rameezdeen, R., Bennetts, H., Wang, Y., Mao, G., ... & Duan, H. (2017). Green building evaluation from a life-cycle perspective in Australia: A critical review. Renewable and Sustainable Energy Reviews, 70, 358-368. https://doi.org/10.1016/j.rser.2016.11.251

32. Giannaros, T. M., Melas, D., Daglis, I. A., Keramitsoglou, I., & Kourtidis, K. (2013). Numerical study of the urban heat island over Athens (Greece) with the WRF model. Atmospheric Environment, 73, 103-111. https://doi.org/10.1016/j.atmosenv.2013.02.055

33. Giannopoulos, A., Caouris, Y. G., Souliotis, M., & Santamouris, M. (2022). Characteristics of the urban heat island effect, in the coastal city of Patras, Greece. International Journal of Sustainable Energy, 41(6), 556-571. https://doi.org/10.1080/14786451.2021.1950722

34. Mihalakakou, G., Flocas, H. A., Santamouris, M., & Helmis, C. G. (2002). Application of neural networks to the simulation of the heat island over Athens, Greece, using synoptic types as a predictor. Journal of Applied Meteorology and Climatology, 41(5), 519-527. http://dx.doi.org/10.1175/1520-0450(2002)041%3C0519:AONNTT%3E2.0.CO;2

35. Kyra Marty, Urban Heat Islands – small scale climate change (2020), retrieved from: https://wp-prd.let.ethz.ch/WP0-CIPRF91243/chapter/urban-heat-islands-small-scale-climate-change/

36. Martin Heemskerck, Hanging Gardens of Babylon (2012, April 26), retrieved from: https://www.worldhistory.org/image/77/hanging-gardens-of-babylon/

37. http://www.greenroofs.com/projects/chicago-city-hall/

38. Scientific Applications International Corporation (SAIC), Curran, M. A., National Risk Management Research Laboratory (US), & Office of Research and Development, Environmental Protection Agency, United States. (2006). Life-cycle assessment: principles and practice. Retrieved from: http://people.cs.uchicago.edu/~ftchong/290N-W10/EPAonLCA2006.pdf

39. https://www.iso.org/obp/ui/en/#iso:std:iso:14044:ed-1:v1:en

40. Διαμαντή Άννα Νεοφίλη, Μεταπτυχιακή διατριβή, Πανεπιστήμιο Δυτικής Μακεδονίας (2023), «Ανάλυση Κύκλου Ζωής πρότυπης ηλιακής θερμικής συσκευής συλλέκτη – αποθήκης θερμότητας».