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MASTERARBEIT

Comparing the impact of Green and Cool roofs

on a building's thermal performance.

A case study for low insulated residential buildings in Greece.

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs / Diplom-Ingenieurin unter der Leitung

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Dedicated to Voula P. and Giorgos P.

Abstract

This Master Thesis is a case study regarding flat roof refurbishment and thermal behavior improvement of residential buildings in Greece. The objective of this study is to explore the abilities of this building type to reduce non-renewable energy consumption and hence obtain an environmental character, which can be extended on an urban level. Houses in hot Mediterranean climates consume large amount of energy in order to cool during the hot summer period. Flat roofs are the most popular way of construction in Greece and in these cases they are the most exposed element of the building's external envelope to solar radiation. This study supports the implementation of green and white cool roofs to aid the housing sector in dissipating the excess heat gains and therefore lowering the energy consumption and even improve the microclimate in urban environments. Both technologies are analyzed on feasibility and economic level, based on previous research. Simulations have been performed in order to test the thermal performance of the different roof technologies and compare their benefits in terms of indoor temperature and cooling and heating loads. Results demonstrate a greater potential in energy loads reduction when green roof is applied on the existing structure and especially for the top floors of the structure.

Keywords: green roof, cool roof, Mediterranean climate, building performance, cooling loads, indoor temperature, EnergyPlus

Zusammenfassung

Dieser Diplomarbeit beschäftigt sich mit den Möglichkeiten der Flachdach Sanierung und den damit verbundenen Veränderungen der thermischen Eigenschaften von typischen Mehrfamilienhäuser (Polykatoikia) in Griechenland. Diese Gebäude bestehen aus einem Betonskelett und sind in den meisten Fällen mit einem Flachdach ausgeführt. Häuser im warmen mediterranen Klima verbrauchen sehr viel Energie für Kühlung während der heißen Sommermonate. In der vorliegenden Diplomarbeit wird der Effekt der Nachrüstung dieser Dächer mit alternativen Möglichkeiten untersucht, speziell wird auf die Implementierung von Gründächern oder Kühlen Dächern (Cool Roofs) anhand eines Gebäudes in Agrinio eingegangen. Mit Hilfe thermische Simulation wird untersucht, in wie weit diese Dächer das Innenraumklima in den verschiedenen Teilen und Stockwerken in einem Mehrfamilienhaus beeinflussen kann. Weiters werden Synergieeffekte der genannten Dachkonstruktionen besprochen und auch die Machbarkeit, bzw. Wirtschaftlichkeit unterschiedlicher Konstruktionsmethoden wird anhand einer Literaturrecherche diskutiert. Die Ergebnisse zeigen eine klare Verbesserung des Innenraumklimas in der wärmeren Jahreszeit in den oberen Stockwerken des Gebäudes. Dies kann zu einer Reduktion der Kühllast führen und somit zu einem geringeren Energiebedarf.

Schlagwörter: Gründach, cool roof, mediterranes Klima, Kühllast

Contents

1. Introduction

1.1 Motivation

With the world temperatures rising at an unprecedented rate, dramatic climatic changes can lead to unbearable summer conditions in urban environments. Urban environments are shown to be significantly warmer than the surrounding landscapes because of the absorbed heat through built surfaces, the lack of vegetation and the heat generated from human activity such as air-conditioning usage, vehicles and industry (GCCA 2012). This phenomenon is called the "urban heat island effect". According to P.J. Crutzen (2000) within 50 years an estimated 80 percent of the world's population will live in an urban area, a prediction that makes addressing this heating effect even more urgent, in order to eliminate energy consumption, protect our environment and ecosystems and eliminate human health risks (Fig. 1).

Figure 1. The Summer Urban Heat Island Effect (GCCA The cool roof toolkit 2012).

In most developing countries the energy usage in the residential sector accounts for a significant percentage of the total energy consumption (Eurostat, 2013). During the last decades residential energy usage is in constant growth. Income levels, natural resources, climate change and the available energy mix are the key factors that affect the energy usage by household in a given country (Tsani 2010, Papathanasopoulos 2010) (Fig.2).

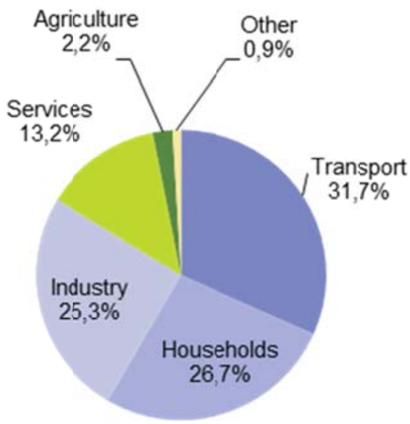

Figure 2. Final Energy consumption per sector. (EUROSTAT 2013)

The majority of Greek cities is characterized by the post-war urbanization and has been developed with apartment building blocks known as "polykatoikia" (Fig.3,4,5). This type of buildings became the city's urban characteristic and now constitute the predominant local architecture of every contemporary Greek city. A typical "polykatoikia" consists of four stories, while occasionally it may exceed six stories (Aesopos et al. 1999). One or more apartments are located in each floor depending on the size of the building. Most of these buildings were constructed under the same building regulations. The building plan is designed to achieve the maximum allowable heights and maximum light penetration (Theodoridou, et al. 2011). Architectural features commonly found on these buildings include balconies along the facade, "piloti" that raise the building to accommodate parking, a flat roof, a central vertical staircase in the core of the building, and light wells to bring light into the lower floors (Theodoridou, et al. 2011). Horizontal circulation is regulated through a long corridor serves the different zones. The apartment can be divided in two parts. The common areas such as the living room face the urban edge of the city, and the more private spaces such as the bedrooms, usually face a private open space (Papamanolis 2005, Paschou 2001)

Figure 3. Apartment building blocks known as "polykatoikia" (*www.buildnet.gr)*

Figure 4. Apartment building blocks known as "polykatoikia" (*www.buildnet.gr)*

Figure 5. Apartment building blocks known as "polykatoikia" (*www.buildnet.gr)*

According to the Hellenic Statistical Authority (EL.STAT 2013), buildings constructed before 1980 represent the 74.6% of the building stock in Greece and are classified in the first category of the building stock that represents buildings with no thermal insulation. The second category consists of dwellings constructed during the period 1980-2001 which in the majority are partially insulated. The third category includes the buildings that were constructed from 2001 up to year 2011. Only the buildings that belong to the last category are well insulated with no thermal bridges and with double glazed windows (Papamanolis 2005, Paschou 2001, Theodoridou et al. 2011).

Energy consumption in non-insulated or low- insulated Greek residential buildings is among the greatest energy consuming sectors. The national energy balance data, available from the Hellenic Ministry of Development report the percentage of energy consumption during the past 40 years. Residential dwellings represent 25% of the total energy consumption of the Hellenic building stock and consume 32.7% of the total electricity produced in Greece. They consume 21.5% of the total energy (ELSTAT 2013) (Fig.6).

The roof is generally the most exposed element of the building's external envelope to the solar radiation and absorbs more than 80% of the sunlight that contacts them. This energy is converted to heat, which can dramatically affect the energy consumption of a building, especially in the case of low insulated buildings. Flat roofs are a dominant way of construction in urban areas in Greece and the main characteristic of the "polykatoikia", making the roof improvements the least invasive and most accessible way of addressing the excessive energy consumption during the hot summer period (Papamanolis 2005, Theodorisou 2011).

The above data on energy consumption and rising urban temperatures, as well as the role of the roof quality on this phenomenon have led to the hypothesis of how efficient can a roof improvement on existing buildings can be and which of the most popular roof cooling techniques can help addressing the energy problem faster, more efficiently and ultimately with minimum cost.

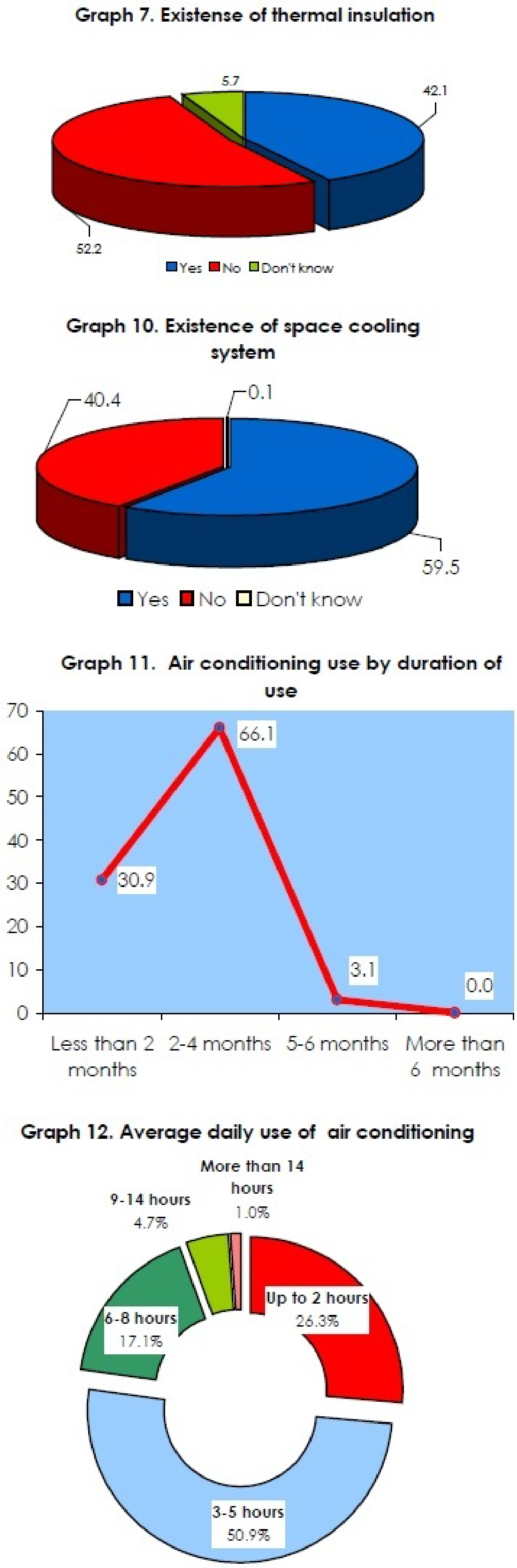

Figure 6. Hellenic Statistical Authority and CRES, Survey on Energy Consumption in Households October 2011 – September 2012 (Hellenic Statistical Authority 2013)

1.2 Objectives

The objective of this study is to explore the potential of the "polykatoikia" - the most common residential building type in urban Greece – to reduce non-renewable energy consumption and hence to obtain an environmental character through minimum refurbishment. The reconsideration and refurbishment of the roof layer is the least invasive method to improve a building's thermal behavior with minimum cost.

Two of the most popular alternative cooling techniques, Green Roofs and Cool White Roofs are selected and examined in terms of cost efficiency and life span, indoor thermal comfort improvement and finally energy loads reduction, after applied on an existing low-insulated residential building in one of the most heat- affected parts of Greece.

Ultimately the scope of this study is to contribute to the existing and ongoing investigation of alternative cooling techniques by trying to answer to the following questions:

- What is the most appropriate passive cooling technique for the particular location and climate?
- What is the optimal configuration of each system?
- What are the anticipated energy savings resulting from its application?
- How much does it contribute in terms of thermal comfort?
- Which solution has more potential in terms of cost efficiency and growing community awareness?

All the above questions will be addressed during this case study and hopefully, combined with all previous and following studies, will grow some more awareness regarding the direction towards more passive energy solutions in the future.

1.3 Background

1.3.1 Cool roofs

1.3.1.1 Historical examples of cool roofs

Historically it is observed that, throughout the evolution of communities, experience and knowledge incorporated in buildings with more simple and maybe not so conscious ways. The traditional builders were forced - in the absence of hardware and material abundance - to adapt the house and the village to the climatic, topographical and general environmental conditions of the location, in the best possible way. The island complex of Cyclades, situated in the Aegean Sea, is a location known for its extreme weather conditions, characterized mainly by intense sunlight, strong seasonal winds, long periods of drought and high levels of humidity.

Avoiding overheating of buildings by minimizing direct heat from the sun was one of the main objectives of the traditional architecture in this area. The white shells of the buildings reflected most of the longwave solar radiation and prevented the indoor spaces from overheating. The white color was used not only on roofs, but also on walls and pavements and the whitewashing of all surfaces was repeated every year, in order to preserve the absolute white. This technique remains and continues to be used until today even in all new constructions (Kalogeras et al. 1989) (Fig.7).

Figure 7. Typical white village in Serifos, Cyclades.

Figure 8. Modern example of white white cool roof (www.enet.gr).

1.3.1.2 Cool roof benefits and technical characteristics

As cool roof is characterized a roof coating system capable of effectively reflecting the solar radiation, resulting in keeping the roof surface cooler under the sun. The effectiveness of the system lies on the reflective properties of the coating material. Cool colored materials reflect the Near-Infrared [NIR] part of the solar radiation and, hence, will be cooler under the sun compared to standard material of the same color that absorbs the NIR radiation (Fig. 9).

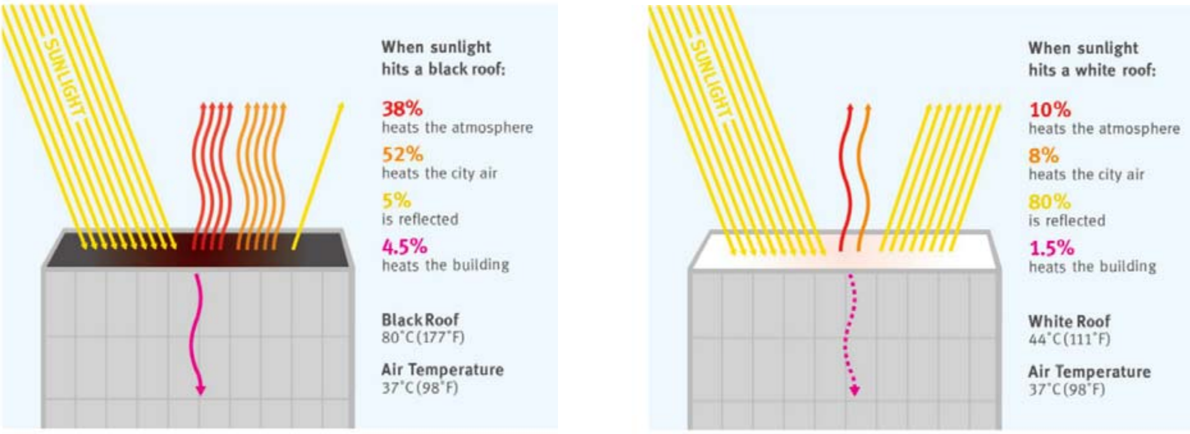

Figure 9. The reflective properties of cool roofs (GCCA The cool roof toolkit 2012).

In air-conditioned buildings, lower surface temperature of the cool roof helps to reduce energy demand in summer time for cooling. In building without air-conditioning, cool roofs improve interior comfort during summer (Levinson, et al., 2006). The advantages of using cool roofs is not only limited to reduction of cooling loads in buildings. The decrease in surface temperatures reduces the flow of heat into the atmosphere, offsetting warming caused by greenhouse gases, while a decrease in urban air temperatures can help slow the formation of ground level ozone and therefore improve air quality (Akbari, et al., 2009).

A large number of experimental and modeling studies demonstrate the benefits of cool roofs, which can be summarized as follows (Santamouris, et al., 2011):

- Reduction of building heat-gain: the temperature of a cool reflective roof typically increases only a few degrees Celsius above ambient temperature during the day.
- Savings on summertime air conditioning expenditures, in conditioned buildings ranging averagely 10-40% depending on building characteristics and use as well as climatic conditions.
- Improvement of thermal comfort conditions in non AC buildings.

- Reduction of peak electricity demand (resulting in downsizing of equipment, reduction of likelihood of power failures on extremely hot days, financial savings for electricity customers who are charged for the largest amount of power (watts) they demand during a billing period).
- Enhancing the life expectancy of the roof system and therefore reducing expenses for maintenance (because of less UV degradation and less thermal fatigue).
- Mitigation of the heat island effect by 1-2 ^{o}C, as less heat is transferred to the surrounding air.
- Reduction of air pollution and CO_2 emissions.

Cool roofs are well known and promoted in the US, while in Europe they became more popular thanks to the Cool Roofs project, which contributed to the foundation of the European Cool Roof Council (ECRC). The objective of the ECRC is to bring together all the relevant actors in the field of cool roofs and merge all the driving forces for the promotion and finally the adoption of cool roofs in the EU (Santamouris, et al., 2011). In the framework of the Cool Roof project in Europe a thorough database was created, where more than 2000 cool roof materials available in the European market are enlisted accompanied by a technical report that includes all related information regarding the material physical properties:

- **Solar reflectance**
- **IR Emittance**
- **Maximum Surface Temperature**
- **Solar reflectance index**

Parallel to the database development five case studies were conducted in order to assess and demonstrate the cool roof potential in terms of improving the thermal conditions in non-air-conditioned buildings as well as reducing the energy consumption in air-conditioned buildings.
Two of the conducted case studies were situated in Greece, in Athens and Crete (2010) and the studied buildings were a non-insulated school and an insulated one-story office building.
Both case studies have shown significantly reduced cooling loads during the summer period up to 27% with a slightly or even negligible higher heating demand during the winter and 1.5-2 ^{o}C reduction of the indoor temperature. Specifically for the case study in Crete the cool roof application was proven to be the most effective solution compared to increased insulation or windows improvement (Kolokotsa, et al., 2011).

Based on the first European market and potential study conducted in the framework of the Cool Roofs project, private residencies are the second most suitable candidates, after public buildings, for cool roof material application. Greece has already embraced the Cool Roof initiative by taking into consideration cool materials and their properties in the new Greek energy code and allowing this way their definition for the estimation of a building's thermal performance.

1.3.2 Green roofs

1.3.2.1 Historical examples of green roofs

The first examples of green roofs date back at the dawn of the agriculture based society during the early stages of the Civilization around 8.000 BC, when men moved from caves and shelters to organized communities. The first houses were built using materials found in abundance in nature, especially plants such as straw were dominant construction materials due to their insulation, stability and waterproof properties. Even later in history, when small villages evolved in towns of thousands of people, vegetated roofs and roof gardens continued to be popular. One of the greatest examples are the Hanging Gardens of Babylon dated around 652-604 BC (Fig. 10), considered today one of the Seven Wonders of the Ancient World. Another great example of ancient green roof applications are the Ziggurats, which were temples built by ancient Mesopotamians with a core of sand confined with closely spaced layers of palm fronds and reeds (Fig. 11).

Figure 10. A 16th-century hand-colored engraving of the Hanging Gardens of Babylon by Dutch artist Maarten van Heemskerck (Wikipedia 2014)

Figure 11. Ancient Mesopotamian Ziggurat (gsibridge 2014)

Later in history, during the Greek - Roman years, vegetated layered structures are more rare and present only in certain locations in Pompey, Phoenicia and the East, while during the Middle Ages and the Renaissance roof gardens are present in palazzos and villas in Italy (Fig. 12).

Figure 12. Piccolomini palazzo, Pienza Italy (regione.toscana 2014)

Moving forward, during the 18th century, sod roofs, roofs topped with soil and planted with grasses and other plants to stabilize the earth on the roof, were part of the Norwegian vernacular architecture. Sod was used due to lack of standard building materials, such as wood or stone, in the prairies. A layer of birch bark was laid down as a sealing membrane, followed by a layer of twigs for drainage, then covered in sod. Sod roofs provided insulation, mitigated damage to the roof from the rain, prevented the roof from rotting, and the root system bound and strengthened the roof structure. A similar sod roof technique was brought to the United States and Canada by Norwegian immigrants (McDonnel 2011).

Figure 13. A sod roof in Milton, North Dakota, built by Ole Myrvik, a Norwegian Immigrant, c. 1896.

(The Library of Congress 2014)

Throughout the years and with the rapid growth of the built environment in cities, green roofs are considered to elevate the quality and aesthetics of the urban context. Modern examples throughout the globe validate the multiple benefits resulting from adding vegetated roof layers on buildings. In Switzerland 100.000.000 m² of roofs are converted in gardens, while in Germany 10% of roofs are vegetated and most municipalities offer strong motivation to citizens in order to adopt green roof strategies in their buildings. Across the Atlantic, in Vancouver Canada the maximum building height limit can be exceeded in case of a roof garden construction and in Tokyo Japan the vegetation of a roof is obligatory in case the area of the roof exceeds the limit of 1000 m² (McDonnel 2011).

In Greece one of the first buildings with vegetated roof, the building of the Ministry of Economics in Athens, was inaugurated in September 2008 (YPEKA 2012). The area of the green roof is approximately 650 m², which is 52% of the total roof area (Fig. 14). One more example also in Athens is the vegetated roof on top of the administration building of ERAS (Electrical Railway of Athens and Suburbs), which added some green in the center of the city (Fig.15).

Figure 14. The roof of the Ministry of Economics in Athens, Greece (athensvoice 2014)

Figure 15. The roof of the administration building of ERAS in Athens, Greece (athensvoice 2014).

1.3.2.2 Green roof benefits and technical characteristics

Green roofs are layered systems comprising of a waterproofing membrane, growing medium and the vegetation layer itself, they may also include a root barrier layer, drainage layer and, where the climate necessitates, an irrigation system. Their main property is that they protect the building's environment through the plants' foliage and the added thermal mass and insulation of the soil layer can result to reduced cooling loads during the summer period. Further benefits resulting from green roof applications are described below.

Stormwater control is one of the major benefits resulting from green roof applications in built environments (Fig.16). When rain falls on forested and open, undisturbed land, water goes through its natural cycle. About 30% of the water reaches shallow aquifers that feed plants, another 30% percolates and nourishes deeper aquifers, and approximately 40% is almost immediately returned into the atmosphere through plant evaporation and transpiration. In metropolitan areas with buildings and streets comprising 75 to 100% impervious surface cover, rainwater is distributed much differently. Only 5% infiltrates to shallow and deep groundwater aquifers and 15% evaporates into the air through vegetation. A staggering 75% of the rainwater becomes surface runoff. In order to offset these reversed stormwater runoff patterns, communities build costly sewer systems. While costly stormwater collection, storage and treatment systems deal with the impacts of sealed surfaces, they fail to address the source of the problem. In many cases, runoff is directly drained — untreated — into open water bodies and receiving streams (Mentens, et al. 2006). This runoff pollutes our rivers and streams. Studies show a direct link between runoff from impervious surface coverage and degradation of water quality in streams. Even relatively low levels of impervious surface cover (10 to 15% of total land area) in a watershed can make it difficult to maintain stream quality (Barnes, et al., 2002). Greater impervious surface coverage (15 to 20% of the total land in a watershed) has been linked to dramatic changes in shape of streams, water quality, water temperature, and the health of the insects, amphibians and fish that live in these streams (Christopherson, 2001). Green roofs can help ease this problem because they absorb and recycle rainwater. The soil layer and plants soak up water that would otherwise immediately run off into storm sewer. On average, 75% of water is retained on an extensive green roof, stored in plants and the soil layer. Only about 25% of water becomes runoff, but this occurs several hours after the peak flow resulting in decreased stress on sewer systems at peak flow periods. Moreover, when the green roof reaches full saturation, excess water slowly percolates through the vegetation layer to a drainage outlet. The soil layer traps sediments, leaves and other particles, treating runoff before it reaches the outlet. Different soil substrates and vegetation provide different water retention capacities. On average, a 0.5 cm deep moss and sedum layer over a 1 cm gravel bed retains about 58% of water, a 1cm deep sedum and grass layer retains about 67%, and a 1.5 cm layer of grass and herbaceous vegetation retains about 71% of water (Greenroofs for Healthy Cities 2014)

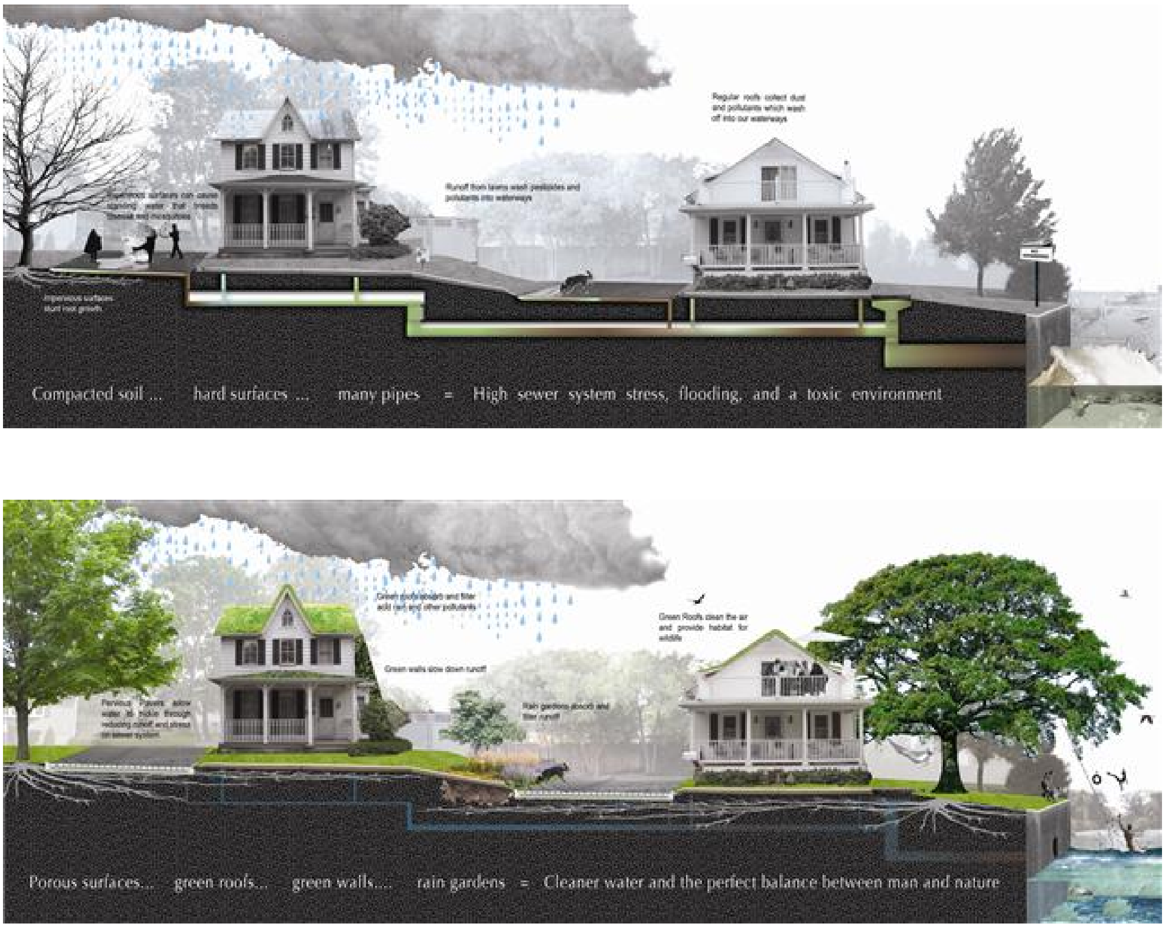

Figure 16. Storm water control and water pollutant removal through green roofs

(Greenroofs for Healthy Cities 2014)

Water pollutant removal is another benefit that occurs through the filtering of particulates out of the rainwater. The pollutant load observed in the green roof outflow is limited, with concentration values for solids and metals lower than those generally observed in storm water runoff from impervious surfaces (Gnecco, et al. 2013)

Mitigation of the urban heat island effect can be another benefit resulting from the extensive use of green roofs in built environments, moderating this way the roof surface temperature and therefore improving the urban microclimate (Alexandri 2010).

Improvement of the outdoor air quality is also possible, through filtering of dust and pollutants out of the air and the conversion of carbon dioxide to oxygen through photosynthesis, which results to making urban environments more sustainable and therefore more livable (Theodosiou 2003).

Noise reduction is claimed to be another result from green roof applications in cities. The combination of soil, plants and trapped layers of air within green roof systems can act as a sound insulation barrier. Sound waves are absorbed, reflected or deflected. The growing medium tends to provide excellent low frequency sound attenuation whilst the plants block higher frequencies. The amount of sound insulation though is dependent on the system used and the substrate depth (TKM 2007).

The Potential for wildlife habitat is higher when specific design principles are met. Mainly the placing of objects associated with natural habitats (local substrates and seeds) can lead to an increase in the biodiversity potential of the roof and therefore an increase of vegetal and animal biodiversity in cities (Grant, et al. 2003).

Enhanced roof membrane durability can also be ensured through the application of a green roof. The additional layers of the vegetated roof protect the construction from exposure to extreme weather conditions and therefore increase its lifetime.

There are two main classifications of green roof **intensive** and **extensive**.

Intensive green roofs are usually characterized by a deeper substrate layer to allow deeper rooting plants such as shrubs and trees to survive. Soil thickness can exceed the thickness of 15-20 cm with large plants growing in deep and hard landscape features such as heavy planters, water elements, and pathways and sitting areas. An intensive green roof system is characterized by its variety of vegetation ranging from herbaceous plants to small trees with professional maintenance and advanced green roof irrigation systems. The design load for this type of green roof is in the range of 200 to 1000 kg/m^2, which is often too high for retrofits on existing buildings without costly structural upgrade (Luckett 2009). This system supports everything from small personal/home gardens to full scale public parks. Plant selection and design greatly affects the maintenance required for the upkeep of these roofs. Rooftop farms, urban roof farms or vegetable farms on roofs are clearly intensive green roofs and require higher nutrient applications and focused maintenance. Furthermore, additional safety measures, such as railings and signage, must be added. These all increase the project costs, making intensive green roofs less attractive for retrofits (Fig.17-18).

Figure 17. Intensive green roof, Chicago City Hall (greenrooftechnology 2014)

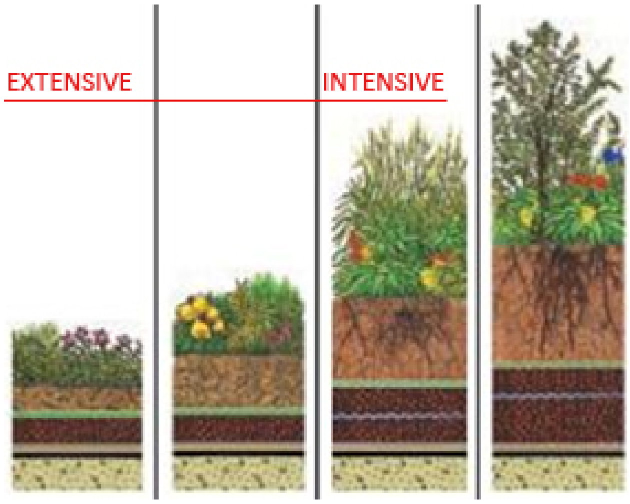

Figure 18. Extensive and intensive green roof systems (greenrooftechnology 2014)

Extensive and semi-intensive green roofs involve smaller plants, typically sedum or lawn, growing on a thin substrate layer (5 to15 cm), with simple hard landscape such as pavers and aggregates. Since the design weight is 50 to 200 kg/m², existing roofs can often accommodate the extra load without structural upgrade (Luckett 2009). Therefore, extensive and semi-intensive green roofs are more suitable for retrofit applications, to tackle energy crises as well as to cover the poor insulation problems in old buildings. These systems are also ideal for efficient stormwater management with low maintenance needs. (Fig.19-20).

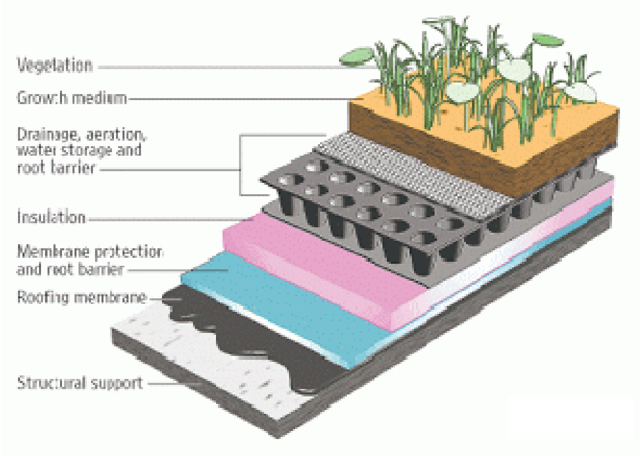

Figure 19. Extensive Green Roof system (The Wall Street Journal 2014)

Figure 20. Extensive Green Roof example (Zinco 2014)

There is a wide range of studies on green roofs and their energy performance, as well as the effect of their different components such as the type of vegetation and growing medium used.

Evmorfopoulou and Aravantinos (1998) proved that by providing large surfaces with vegetation, they contribute to the improvement of thermal performance of building. This finding was supported by Niachou, et al. (2001) which discovered the indoor temperature values in the building with green roof are lower during the day. They measured the roof temperatures in non-insulated building with and without green roof. The result shows that the surface temperature of non-insulated building without green roof vary from 42 to 48 ^{o}C while the surface temperatures of the green roof upon non-insulated building are lower and ranging from 28 to 40^{o}C. They also concluded that the existence of large temperature differences due to the installation of green roof could contribute to a substantial energy saving potential for non- or low- insulated buildings. Their conclusion was also validated by the research of Wong et al (2003), who also observed that the green roof better benefits buildings with poorer roof insulation. Spala et al. (2008) found that the installation of green roof on the office building in Athens presents a significant contribution to the energy saving during summer period. The remarkable reduction of building cooling load was estimated during the simulation study. However, during winter, the effect of green roof installation is not significant because the reduction of the heating load was quite small.

Many researches have also estimated that plants and substrates are a major contributor to the thermal performance and energy reduction aspect of the green roof.

1.3.2.3 The Green Roof vegetation layer

Many studies had proved that different kinds of vegetation could give different thermal reduction measurements. Large foliage development with mainly horizontal leaf distribution could give excellent thermal reduction (Del Barrio, 1998). Niachou et al (2001) discovered that surface temperature of green roof varies with different types of vegetation. Lowest temp was measured in the space with thick dark green vegetation. That finding was supported by Wong et al (2007) which indicated that the temperatures measured underneath the relatively extensive greenery coverage were relatively lower than that measured underneath the groundcover with tiny leaves. Lower temperatures were measured under thick foliage while higher temperatures were obtained under sparse vegetation or only soil, and green plants irradiated and reflected less solar heat (Wong et al., 2003).

The selection of plants to be planted on the roofs depends on to the final plant height required, their flowering period and the type of soil these particular plants needed (Spala et al., 2008). This finding was strongly supported by Theodosiou (2000). Theodosiou had discovered that foliage height is strongly influenced by the transpiration levels and related to the shading of the soil surface. The shorter the foliage height, the stronger the thermal connection between them. However, on the days of continuously high temperatures, the high foliage still contributed to the removal of thermal loads from the building interiors. Foliage density also plays an important role in energy phenomenon. Large perimeter values could practically completely shade the lower foliage area and the soil layer surface, thus protecting it from solar radiation (Theodosiou, 2000).
Green roof plants should also be tougher and need fewer nutrients than plants found in most gardens. Low growing, shallow-rooted perennial plants that are heat, cold, sun, wind, drought, salt, insect and disease tolerant are the most successful green roof plants (Snodgrass, 2006).

1.3.2.4 The Green Roof substrate

Substrates or growing media can influence plants establishment and performance under various conditions. Different factors of substrate such as type, depth, slope and irrigation can result in different performance of the green roof.

According to Snodgrass (2006), the green roof medium must be substantially lighter, less rich and more porous than soil used for ground-level garden. Del Barrio (1998) used a mathematical model to assess the summer cooling potential of green roofs in Athens, Greece. She found that the thickness of the soil layer, its relative density, along with moisture content, influenced the thermal diffusivity of the soil. As the density decreased, the thermal conductivity of the soil decreased, hence the heat flux through the roof decreased. Additional air pockets in the less dense soil increased its insulating properties. As far as the moisture content is concerned Del Barrio (1998) concluded that moisture enhances the insulation properties of the soil, a conclusion contradicting to the most logical findings of Wong et al. (2003) and Alcazar and Bass (2005), who concluded that wetter soil is a poor insulator compared to dry soil, a more reasonable conclusion considering that water is a better conductor than air.

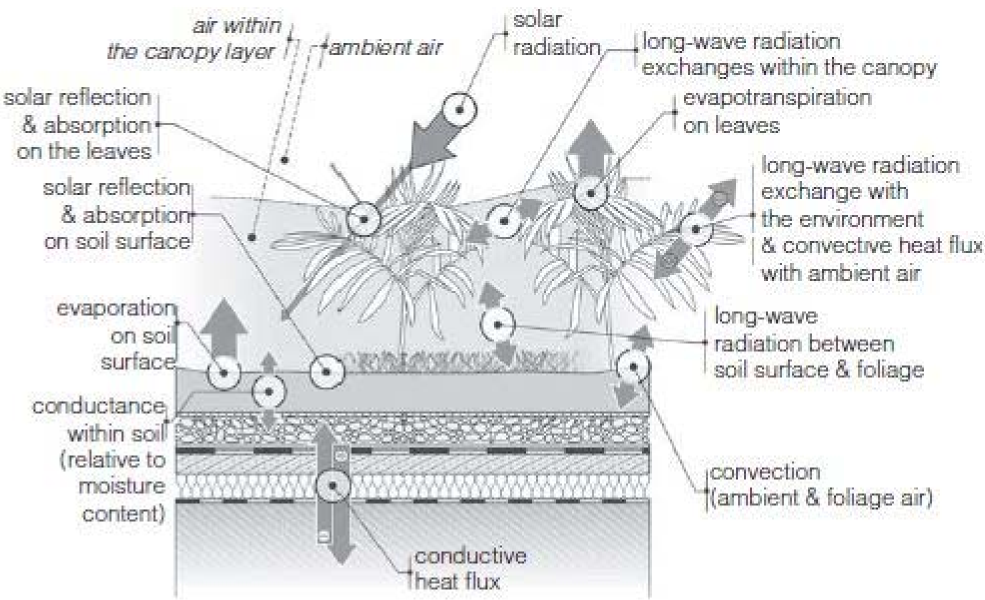

Figure 21. The energy balance for a green roof.

(Advances in energy building research 2009, volume 3, p.275)

1.3.3 Cost efficiency, benefits and feasibility

1.3.3.1 The Cool roof potential

A wide range of materials can be combined with different roof constructions in order to create a cool roof, such as clay shingles with high albedo values, cool shingle-ply roofing systems and cool elastomeric or cementitious cool coatings. This facilitates the conversion of existing roof constructions, as existing rooftops can be easily covered or painted in order to change their albedo.

Cool roofs are usually low cost investments, especially if the roof needs replacement or upgrade anyway, the choice of a white colored material often costs the same as a dark colored typical alternative. The same applies for the labor required to install or coat cool roofs, which is practically the same as for non-cool roofs.

According to Santamouris et al (2011) the lifespan of cool roofs is usually longer than in the case of non-cool roofs, due to lower surface and material temperatures and the lower temperature differences. One more parameter to be considered is the fact that the performance of the cool surface can decrease overtime because of dust and biomass deposit, which result to a reduction of the solar reflectance abilities. However, according to Synnefa et al. (2007) the resulted attenuation, which is mostly a result of dirt accumulation, is not permanent. After observing the outdoor aging process of several cool materials for a three-month period, they proved that by washing the samples, 93% of the initial solar reflectance was restored. According to the "Cool Roof Toolkit" the maintenance costs for cool roofs is similar to those of a typical roof, while some cool coating materials include some special chemicals that prevent mold or algae growth.

One more economic benefit resulting from the cool roof application is the fact that the lifetime of the whole roof construction can be prolonged. By their ability to maintain a lower average surface temperature, the heat-related degradation of the construction can be significantly delayed.

On an urban and global scale have also been proven to be effective on many different levels. By reducing the fraction of incident sunlight that is converted to heat by the roof, cool roofs can help cool buildings, reduce the urban heat island effect and can even mitigate global climate change.

According to J. Sproul et al. (2013) apart from cooling energy savings, cooler roof surfaces also mitigate the urban heat island effect, which improves air quality, reduces Greenhouse Gas emissions from power plants and increases grid liability during the summer, an argument also previously suggested by Akbari et al. (2001).

On a global level Sproul et al. also noted that increasing the solar reflectance of roof surfaces reduces the amount of heat absorbed at earth's surface and transferred into the atmosphere, an effect that, on a larger scale, can help address the global warming phenomenon.

Based on all the above facts, it can be concluded that cool roofs are a cost effective solution for the end user as well as an environmentally friendly solution on both local and global scale.

1.3.3.1 The Green roof potential

Being part of the building shell, a green roof influences thermal flux through the area it occupies. In contrast with every other building element, the gardening layers of the green roof (soil and vegetation) are a living system that interacts both with the building and the environment in a variety of different ways (Theodosiou 2009).

The growing urbanization, the deterioration of urban climate conditions, and therefore the need for more sustainable urban buildings, have prompted scientists to investigate the green roof technology in an effort to exploit and maximize the contribution of green roofs to the energy performance of buildings.

Based on previous research it is proven that the presence of a vegetated roof can reduce cooling loads during the summer period and therefore contribute to the energy efficiency of buildings. However the contribution of green roofs is not limited only within the building sector. In many scientific studies that examine the urban heat island (UHI) effect, 'cool' roofs and vegetation are regarded as the most effective measures that could upgrade the urban climate if they were applied to a large section of a city's surface area (Santamouris, 2007). Previous research has shown that green roofs can balance out one of the major factors that cause the UHI effect, that of overheated urban surfaces.

Bass et al (2003), using a mathematical model, calculated that a 50 per cent extensive green roof coverage without installation of irrigation systems in Toronto would cool the ambient air by 1°C in summer. If all these roofs were regularly irrigated, then the cooling effect would be 2°C over the area where the green roofs were installed and 1°C over a larger geographical area. In a US Department of Energy report, Tanner and Scholz-Barth (2004) noted that because green roofs absorb most of the incident solar radiation, they can provide similar effects to 'cool' roofs without reflecting solar radiation to taller adjacent buildings that could cause an additional cooling load, glare and discomfort to their occupants. Wong et al (2003) measured air temperature and mean radiant temperature at various heights above a green roof canopy and above a bare roof and found an air temperature decrease of 4.2°C and an MRT decrease of 4.5°C over the green roof. In higher positions the cooling effect was limited, perhaps because of the relatively small size of the green roof. Takebayashi and Moriyama (2007) measured surface temperatures on bare roofs with high reflective coatings and on a non-irrigated green roof in Japan. They found that the cooler surface was that of the high reflective coating, followed by foliage temperature of the green roof (1–2°C warmer). The temperature of the other surfaces was higher by several degrees. They also reported that the surface temperature of the green roof was expected to be lower in summer.

Surface temperature measurements in two extensive green roofs in Germany showed that wet soil layers are capable of maintaining a 5°C lower temperature compared with dry conditions (Köhler et al, 2003). Alexandri and Jones (2007) used a two-dimensional model to study the effect of green roofs and walls in the urban climate. They found that due to the redistribution of radiation within the canopy layer, the total radiative heat exchanges were smaller on the green roof compared with a bare roof. If green roofs were installed over a wide urban area, air masses entering the urban canyons would be cooled by the vegetation and there would be a temperature drop even at street level. The authors conclude that the contribution to air cooling is more intense in hot and dry climates like Athens, but even humid regions can benefit from air cooling through green roofs. However due to their limited reflected properties compared to cool roofs they would have a negligible effect on global temperature even if they were to be widely implemented (Fig.7). Furthermore the effectiveness of green roof technology is not as extensively investigated as the one of cool roofs.

Moving further from the contribution in the building sector and the local scale mitigation of the UHI effect green roofs have a significant potential for precipitation and surface water runoff management. Compared to bare roofs they provide permeable surfaces, which have the ability to retain short term rainwater and, depending on the drainage system, they can even reduce the amount of rainwater that reaches the mostly overloaded urban drainage system. Thomson and Sorvig (2000) measured a total of 18 liters of rainfall reaching the ground after a 10 mm rainstorm, where 200 liters of rain fell onto an 18 m^2 green roof. Depending on the green roof's construction, the climate and precipitation characteristics, the rainfall retention capability on a yearly basis may range from 75 per cent for intensive green roofs equipped with a drainage layer to 45 per cent for extensive green roofs (Mentens et al,2006). On an urban scale, the widespread implementation of green roofs could be part of a city's storm water management policy. As such, many municipal storm water management companies provide a discount to the utility fee like Portland's Clean River Incentive and Discount program (CRID) in the US (Liptan, 2003).

One more major advantage for communities and even cities is the air quality improvement that can be achieved by the vegetation on roofs. Currie and Bass (2008) report that shrubs on green roofs can be as effective as trees in removing PM10 (particulate matter 10 µm or less) when green roofs are installed in sufficient quantities. Field measurements on a 4000 m2 green roof in Singapore showed that the levels of particles and SO2 in the air above the green roof were reduced by 6 and 37 per cent, respectively (Tan and Sia, 2005). Yang et al (2008) modelled the air pollutant uptake by 19.8 hectares of green roofs in Chicago and estimated the uptake of four air pollutants (O3, NO2, PM10, SO2) to be 52, 27, 14 and 7 per cent, respectively. Besides these direct effects of rooftop vegetation, the decrease in surface temperature caused by green roofs can lead to a reduced production of atmospheric ozone (Taha, 1996). In all cases, the ability of green roofs to improve air quality was found to be site specific and in order to affect the urban air quality, policies that would encourage widespread implementation of green roofs throughout an urban area are required.

Going further and investigating the economic feasibility of green roofs among the major disadvantages of this technology are the relatively high initial cost and the additional building load that must be supported. In the case of existing buildings, this limits the choice of green roof type to the extensive type, which in many cases does not need additional support. The major factor that increases the initial cost is the relatively low penetration of green roofs into the market in many countries and especially in Greece, which results in higher construction costs and makes such a construction more expensive than northern Europe or some Asian countries. This is also the main reason, according to a US study that took into account the economic benefit from storm water management and air quality improvement, for green roofs to be 10–14 per cent more expensive than bare roofs throughout their lifetime (Carter and Keeler, 2008).

In any case, the contribution of green roofs is considered to be significant only where there is widespread implementation of green roofs, an action which obviously requires properly planned urban policies. In Tokyo, Japan, private buildings larger than 1000 m2 and public buildings larger than 250 m2 are required to have a green roof that covers at least 20 per cent of the total roof surface. By January 2005, 54.5 ha of green roofs had been installed in the city (TKM, 2007). In Germany, where the construction of green roofs in many cities is enforced by local building regulations, 13.5 million m2 per year is added to the existing green roof coverage (Oberndorfer et al, 2007). In Toronto, Canada, the city has approved a policy that requires green roof constructions covering 50–75 per cent of a building's footprint, whereas in Portland, Oregon, the requirement is 70 per cent (Carter and Fowler, 2008).

All the above examples prove that in order to initiate more awareness on all the public benefits provided by green roof implementation and overcome the cost barriers, a significant amount of support by municipal authorities and by appropriate legislation as well as certain financial measures are required.

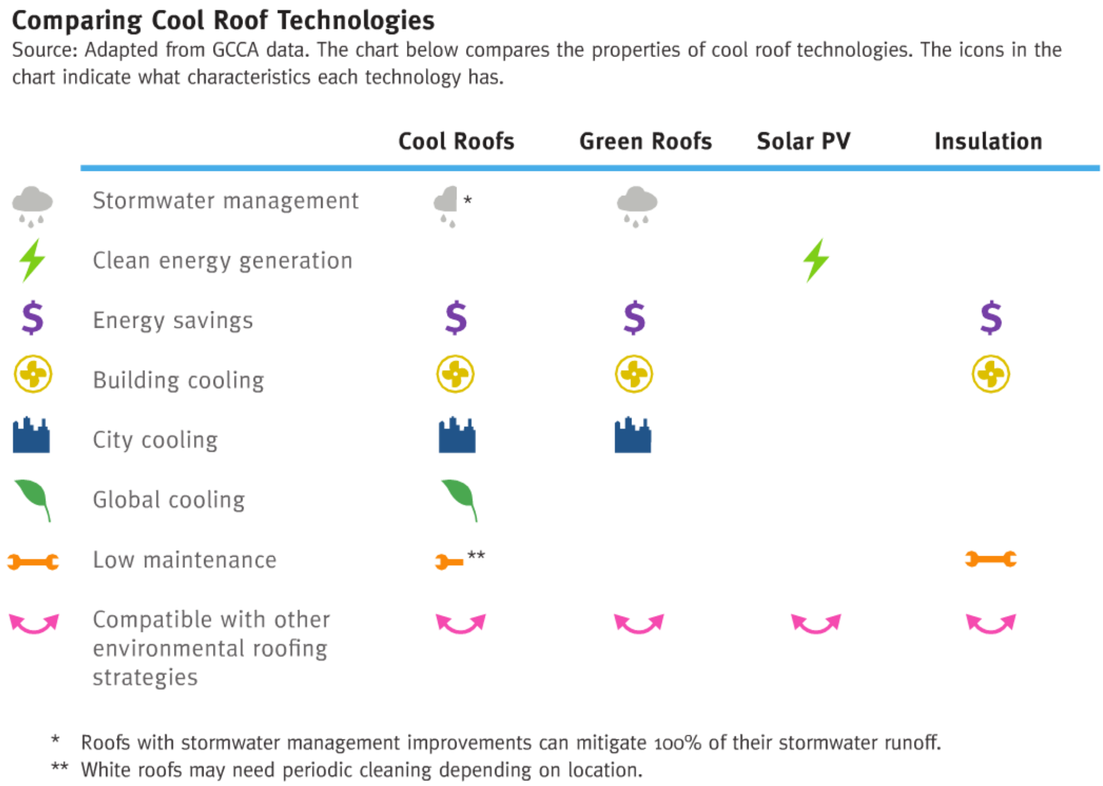

Figure 22. Comparison of different roof technologies. (GCCA The cool roof toolkit 2012).

2. Methodology

2.1 Simulation tools

A wide range of software was considered for conducting the research simulations. Since the simulation input data was simple and concerned mostly typical materials and constructions combined with occupancy and operation schedules, finding the right simulation tool wouldn't be difficult. However, when the green roof component was introduced to the research, it was necessary that the simulation program efficiently models and takes into account the multi- layered green roof technology.

Based on that necessity the EnergyPlus simulation program (EERE 2013) was selected, which introduces the ecoroof component in the materials input data. The component was generated by Sailor (2008), who identified that the already existing mathematical models, developed to calculate the energy transfer through green roofs, simplify the effects of evapotranspiration and time-varying soil thermal properties. It was further noted that architects and developers need a user-friendly design tool to aid in a numerical assessment of green roof benefits. Sailor's 'EcoRoof' model option enables the user to add a green roof as the outer roof layer on any roof building construction.

The green roof is modeled as a single vegetation layer on a soil surface. The vegetation layer model is a steady-state semi-infinite plane panel characterized by an emissivity, albedo, height and foliage fractional coverage that influences the heat exchange between the soil layer and the adjacent air. Soil is modeled as a homogeneous layer through which sensible and latent heat flux pass (Energy Plus Engineering Reference 2013). The green roof model accounts for the following phenomena (Fig.23):

- Long wave and short wave radiative exchange within the vegetation layer including the effect of multiple reflections between vegetation and soil layers.
- Vegetation layer effects on convective heat transfer.
- Moisture effects and evapotranspiration from the soil and plants.
- Heat conductance and storage in the soil layer

(Energy Plus Engineering Reference 2013)

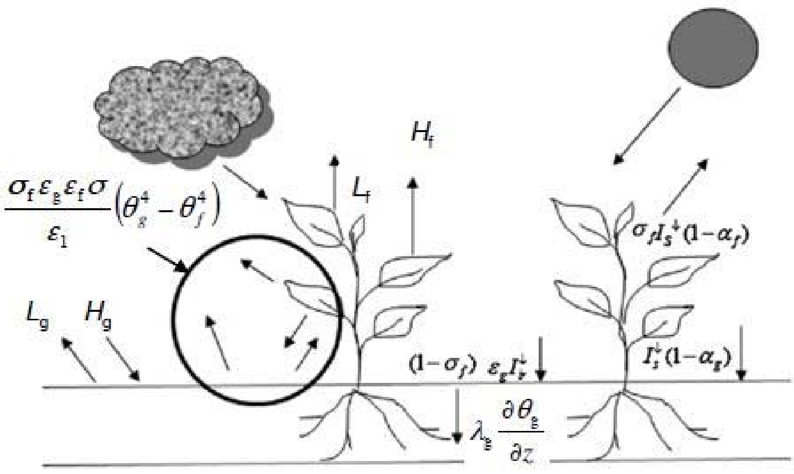

Figure 23. The energy balance for a green roof (Energy Plus Engineering Reference 2013)

Using the Roof vegetation component, will require providing the software with the following information as described on Table 1.The geometrical model of the building was created using the OpenStudio plugin (NREL 2014) for Sketchup (Trimble 2013), which allows the model export in EnergyPlus (EERE 2013).

INPUT DATA	VALUE RANGE + DESCRIPTION
Height of plants (m)	0.005 < H < 1
Leaf area index (dimensionless)	Projected leaf area per unit area of soil surface 0.001 < LAI < 5
Leaf reflectivity	The fraction of incident solar radiation reflected by the individual leaf surfaces 0.05 < LR < 0.5
Leaf emissivity	The ratio of thermal radiation emitted from leaf surfaces to that emitted by an ideal black body at the same temperature 0.8 < LE < 1.0
Minimum Stomatal Resistance (s/m)	Resistance of the plants to moisture transport 50 < MSR < 300
Soil layer roughness	The relative roughness of soil layer

Soil thickness (m)	0.05 < ST < 0.7
Conductivity of dry soil (W/mK)	The thermal conductivity of dry soil
Density of dry soil (kg/m3)	300 < DS < 2000
Specific heat of dry soil (J/kgK)	The specific heat of the soil layer in dry condition
Thermal absorptance	The fraction of incident long wavelength radiation that is absorbed by the material 0 < TA < 1
Solar absorptance	The fraction of incident solar radiation absorbed by the material 0 < SA < 1
Visible absorptance	The fraction of incident visible wavelength radiation that is absorbed by the material 0.5 < VA < 1
Saturation volumetric moisture content of the soil layer	0.1 < SVMC < 0.5
Residual volumetric moisture content of the soil layer	0.01 < RVMC < 0.1
Initial volumetric moisture content of the soil	0.05 < IVMC < 0.5
Moisture diffusion calculation method (2 options)	**Simple**: The original ecoroof model based on a constant diffusion of moisture through the soil, through simple division of the soil in two layers. **Advanced***: The later ecoroof model based on the moisture redistribution model described by Marcel G Schaap and Martinus Th. Van Genuchten. * requires a minimum of **20** timesteps in hour for the simulation.

Table 1. Energy Plus input data for the EcoRoof component (Energy Plus 8.1)

2.2 Region and Climate

2.2.1 Region of study

The region of study is placed in Agrinio city with coordinates 21°21'11"E, 38°36'21" N and altitude 24m (Fig.24). For the study and analysis of the energy efficiency of the sample buildings during the whole year we need the mean hourly values of different climatic parameters in order for the simulation program to extract as accurate results as possible.

Fig.24. Map of Greece indicating the location of the studied building.

As these values are not provided extensively from any weather institution for the region of study we collected the meteorological data for the year 2012 through the usage of the software for meteorological references Meteonorm v.7.0 of Meteotest. This software extracts hourly values for the parameters needed based on excited measurements of the nearest weather stations. After the application of the location coordinates in Meteonorm analytical data for outdoor temperature, solar radiation, relative humidity, precipitation, wind speed and direction were obtained.

2.2.2 Outdoor temperature

For the description of the climate conditions of the region one of the most important parameters that should be taken into consideration is the outside temperature. The Fig.25 gives us information for the mean monthly temperatures during the whole year and the minimum and maximum values. It is obvious that the highest temperature display is 34°C on August whereas the lowest is 3.4 ^{o}C on January.

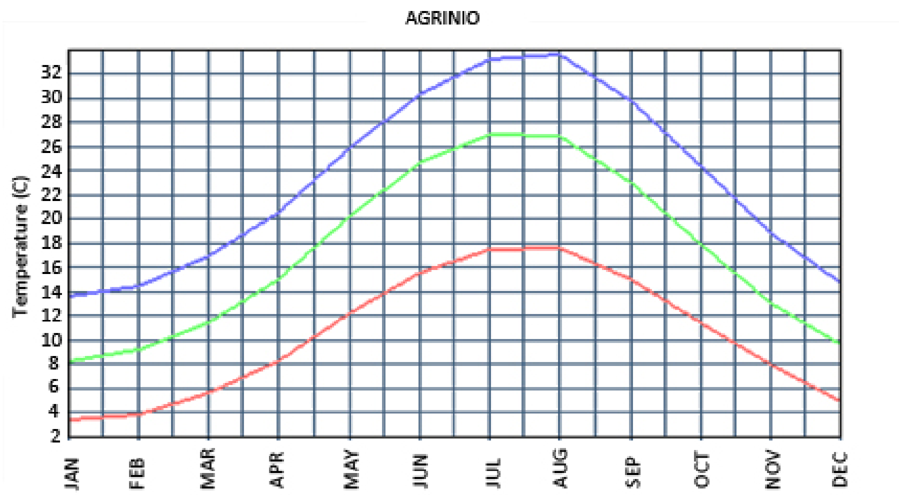

Figure 25. Maximum, mean and minimum monthly recorded site temperature for 2012 (Meteotest 2012)

2.2.3 Solar radiation

Meteonorm (Meteotest 2012) uses the recorded mean monthly values for solar radiation in order to calculate the monthly values of diffuse and global radiation. For the representation of the retrieved results a chart was created (Fig.26), where the x aches represents the months of one year and the y aches the horizontal average direct, diffuse and global radiation in kWh m^{-2}.

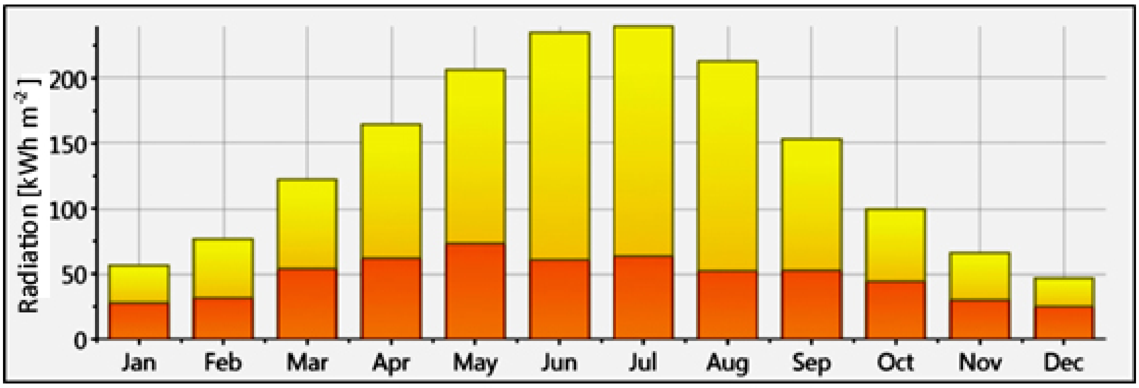

Figure 26. Mean monthly values of solar radiation for 2012.

From Fig.27 it is obvious that the solar radiation in the region of Agrinio reaches its peak during the summer months as the position of the sun is higher above the horizon at any given time of the day and the daylight duration becomes longer.

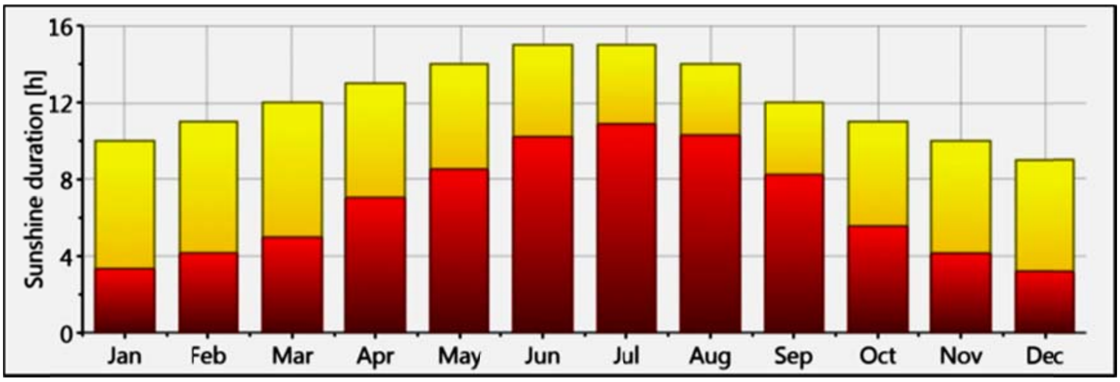

Figure 27. Monthly sunshine duration for 2012 (Meteotest 2012).

2.2.4 Precipitation

Based on the Meteonorm v7.0 (Meteotest 2012), values for the mean monthly precipitation in the studied area the height of rainfall for every month is presented in the Fig.28 and ranges from 14.2 to 99.9 mm. The driest period in 2012 was during the summer months (June to September), whereas during autumn and spring (November to April) the highest rainfall in the region is recorded.

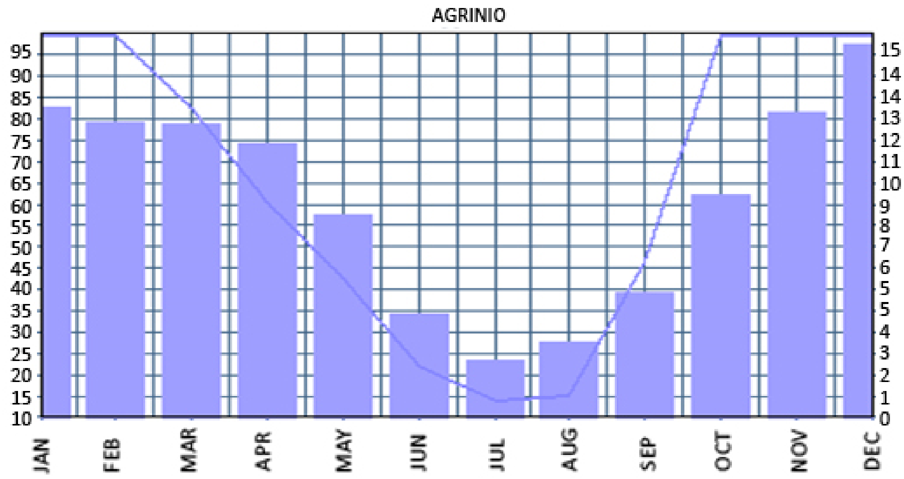

Figure 28. Mean monthly precipitation for 2012 (Meteotest 2012).

2.2.5 Wind speed and direction

The wind speed and direction is also an important climatic parameter for the study of the energy efficiency of the sample buildings, though, the accurate simulation of the speed is inapplicable as it is a constant dependent of the specific geomorphological form and spatial arrangement of the buildings in the region. However, Meteonorm (Meteotest 2012) simulates the wind speed through the combination of a daily model based on average daily global radiation, and on an independent stochastic model (Meteonorm Handbook part III). As we can see in Fig.29 the wind speed occurs during almost the whole year is steady and its values is 2m/s.

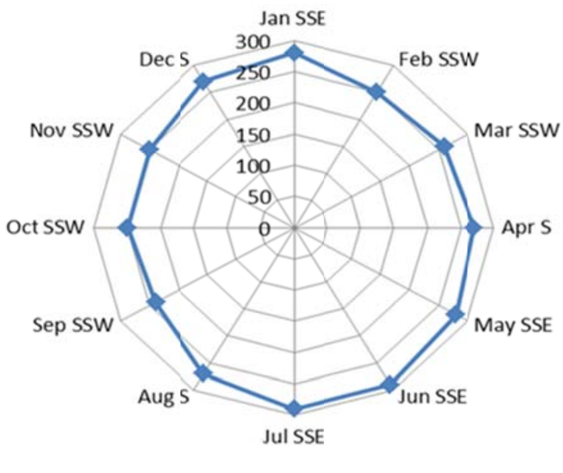

Figure 29. Wind speed values for 2012 (Meteotest 2012).

2.2.6 Relative humidity

In Fig.30 the mean values of monthly outdoor relative humidity are presented. It is obvious that the highest percentage of humidity is recorded in November with almost 80%, whereas in July it reaches its minimum with 55%.

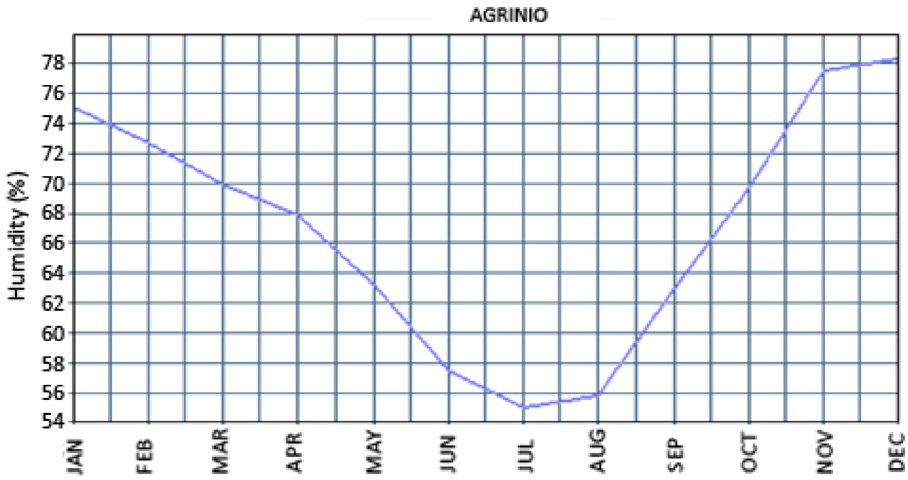

Figure 30. Wind speed values for 2012 (Meteotest 2012).

2.3 Geometry and Technical characteristics of the studied building

The case study building, situated in Western Greece, in the city of Agrinio, is a 5- story residential building with flat roof constructed in the middle 80's.

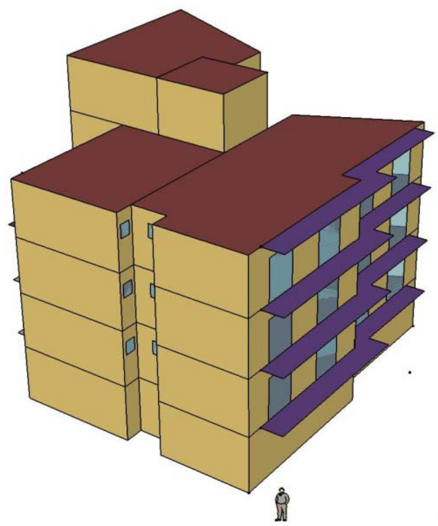

Figure 31. Building model created by the author in OpenStudio (NREL 2014).

The ground floor comprises of the main building entrance and some storage rooms with total area of 203 m².Each floor has two apartments, one family apartment for 4 people with total area of 163 m² and a studio apartment for one person with total area of 54 m², with the exception of the 4th floor with only one studio apartment. Finally, a staircase with lift connects all the floors from ground to roof.

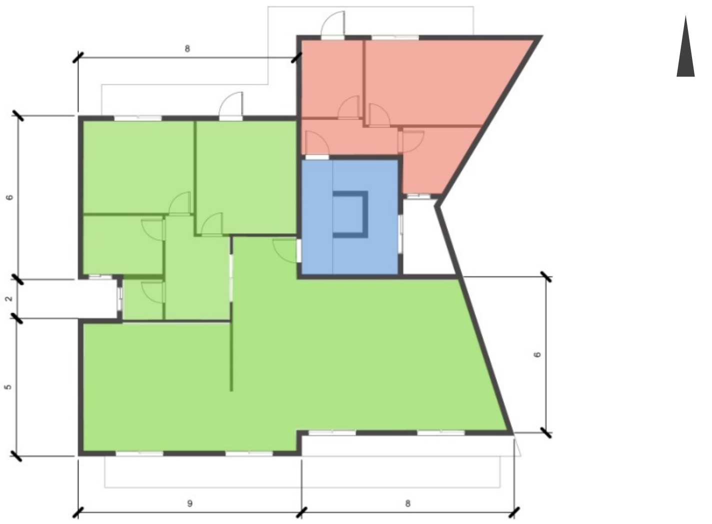

Figure 32. Typical floor plan of the studied building.

The construction of the building dates back in 1984 and is a concrete bearing construction with brick masonry and double aluminum glazing systems. The roof element of the building is a simple concrete beams slab with an interval of 1m between the concrete beams and insulation layer of 20 cm in-between the cavities. The top exterior layer is a concrete based terrazzo, which formulates a smooth finishing surface. The parts of the roof with the uninsulated concrete beams are 17% of the total roof with a U-value of 2.18 $Wm^{-2}K$ and the rest 83% of the roof with the insulated concrete slab has a U-value of 0.616 $Wm^{-2}K$ (Fig.34). As a simple approach to address the thermal bridge effect in the roof construction and based on these values and ratio the roof model is divided in two parts each assigned with two different constructions (insulated with 20cm concrete slab and non-insulated with 40 cm concrete). A more detailed list of constructions and materials is described in Table 2.

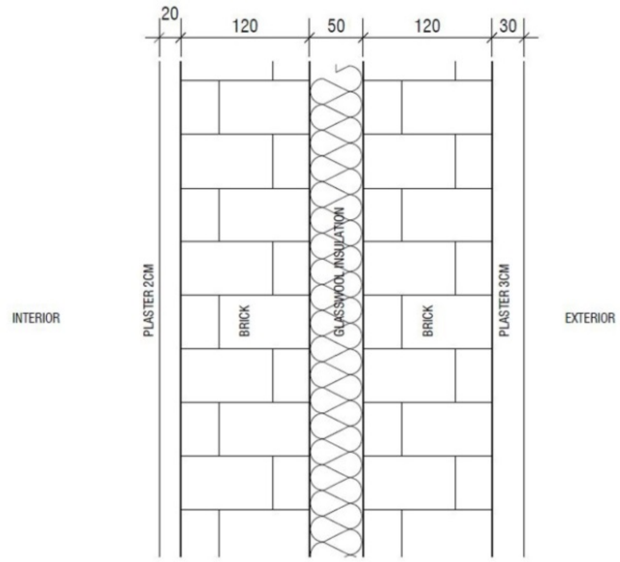

Figure 33. External brick wall construction detail.

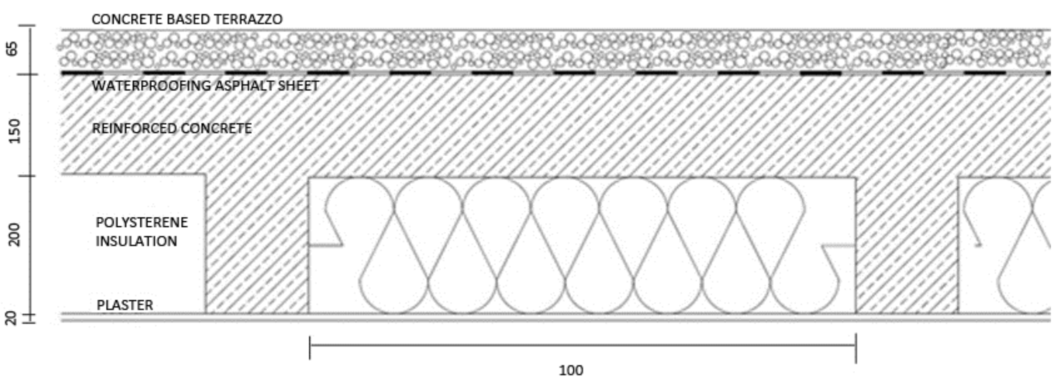

Figure 34. Roof construction detail.

Figure 35. The flat roof of the studied building.

The windows are double glazed (6mm void) with 30% of aluminum non insulated frame with U-value 4.5 $Wm^{-2}K$ and g-value 0.48 as calculated based on the Greek regulation T.O.T.E.E. 20701-1 (p.82, Table 3.12), provided from the technical chamber of Greece.

Attached to the windows are manually regulated aluminum blinds with horizontal slat orientation and a constant slat angle of 20⁰. The operation of the blinds is based on the respective schedule described in paragraph 2.6 Table 9.

Outside Wall:	Thickness [cm]	Conductivity [W/mK]	Thermal Resistance	U-value [W/m²K]
Exterior Plaster	3	1,4	0,021	
Brick	12	0,7	0,171	
Insulation [Glass wool]	5	0,032	1,563	
Brick	12	0,7	0,171	
Interior Plaster	2	0,7	0,029	
			1,955	
Surface Resistance_Rsi			0,130	
Surface Resistance_Rse			0,040	
			2,125	0,471
Roof:				
Terrazzo_Concrete based	6,5	1,5	0,043	
Roof Paper	1	0,23	0,043	
Concrete Slab	20	2,3	0,087	
Insulation [Polysterene]	20	0,16	1,250	
Interior Plaster	2	0,7	0,029	
			1,452	
Surface Resistance_Rsi			0,130	
Surface Resistance_Rse			0,040	
			1,622	0,616
Floor to Ground				
Floor_Wood	2	0,17	0,118	
Concrete [Estrich]	8	1,4	0,057	
Foil [PAE-Folie]	0,2	0,23	0,009	
Insulation	10	0,04	2,500	
Concrete Slab	20	2,3	0,087	
Gravel	10	2	0,050	
			2,820	
Surface Resistance_Rsi			0,130	
Surface Resistance_Rse			0,040	
			2,990	0,334
Inside Wall				
Plaster (Innenputz)	**2**	0,7	0,029	
Masonry (Ziegel)	12	0,7	0,171	
Plaster (Innenputz)	2	0,7	0,029	
			0,229	
Surface Resistance_Rsi			0,130	
Surface Resistance_Rse			0,130	
			0,489	2,05
Floor/Ceiling				
Floor_Wood (Parkett)	2	0,17	0,118	
Concrete (Estrich)	8	1,4	0,057	
Foil (PAE-Folie)	0,2	0,23	0,009	
Insulation	5	0,04	1,250	
Concrete	20	2,3	0,087	
Plaster (Innenputz)	2	0,7	0,029	
			1,549	
Surface Resistance_Rsi			0,130	
Surface Resistance_Rse			0,040	
			1,719	0,582

Table 2. Materials and constructions properties .

2.4 Applied roof technologies

2.4.1 The Green Roof

The green roof applied and analyzed in this study is a multilayer extensive green roof commonly used in the Mediterranean region with no extra insulation layer. The new layers of the green roof element are laid right above the existing construction, a moisture barrier, a drainage layer, a filter layer, a soil layer and vegetation layer as shown in Fig. 36.

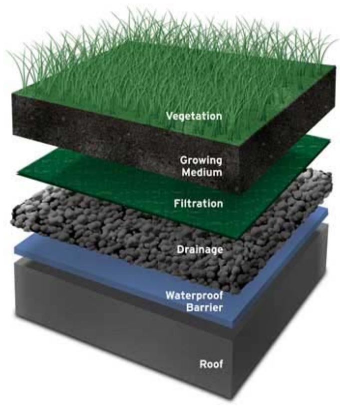

Figure 36. Green roof layers (prasinistegi 2014).

2.4.1.1 Soil layer

The composition of green roof soil is significantly different from naturally occurring soil. It must allow the growing of thick roots while satisfying the natural, chemical and biological needs of the plants. It is also required to be stable and with high water storage qualities - so that a minimum amount of water leaks to the drainage layer - while enabling the ventilation of the root system even when its humidity levels reach peak values (Sailor, et al. 2008).

This resulted in a market research on green roof soil composition. Compared to the common types of soil, green roof soils are characterized by a low quantity of organic compost, by a relevant quantity of sand and a very high quantity of lightweight inorganic aggregate. The lightweight inorganic aggregate is highly porous, which leads to lower weight of the green roof, but also allows a greater storage of water, while the organic compost component also enhances the water storage properties of the soil. For this reason this kind of soils are generally characterized by low values of thermal conductivity.

Reaching a point where the thermal properties of the green roof soil were needed for the simulation, further research was conducted in order to obtain the input data requested by EnergyPlus. Generally few data about green roof soils are available: technical standard EN ISO 13370 (CEN 2007) provides thermal characteristics of few common soils which are not used as green roof growing media. On the other hand Sailor et al. (Sailor et al., 2008) monitored eight types of ecoroof soils commonly used for green roofs in the United States with different moisture levels in order to obtain values of density, thermal conductivity, specific heat and albedo. The composition of the eight types of soil is reported in Table 3 while the thermal properties of soils characterized by zero per cent of moisture level content are reported in Table 4.

Soil Code	Pumice [%]	Expanded Shale [%]	Compost [%]	Sand [%]
DH01	50	0	10	40
DH02	50	0	0	50
DH03	75	0	0	25
DH04	75	0	10	15
DH05	0	50	10	40
DH06	0	50	0	50
DH07	0	75	0	25
DH08	0	75	10	15

Table 3. Composition of green roof soils (Sailor et al., 2008).

Soil Code	P_g [kg/m³]	λ_g [W/(m*K)]	c_p [J/(kg*K)]	α_g [-]
DH01	1020	0.17	1093	0.28
DH02	1130	0.18	1032	0.41
DH03	880	0.17	1227	0.38
DH04	760	0.14	1251	0.39
DH05	1360	0.20	887	0.17
DH06	1400	0.21	890	0.19
DH07	1117	0.20	966	0.18
DH08	1060	0.18	1093	0.18

Table 4. Thermo-physical properties of green roof soils for 0% of moisture level (Sailor et al., 2008).

2.4.1.2 Vegetation Layer

For the purpose of this case study the soil sample DH08 of Sailor with a width of 10 cm was selected based on its similarities to the extensive green roof soils located on the local market. Furthermore it is considered critical at this point of the research to collect also the rest of the necessary input data regarding the vegetation layer properties.

The vegetation layer model in EnergyPlus (EERE 2013) is a steady-state semi-infinite plane panel characterized by an emissivity, albedo, height and foliage fractional coverage that influences the heat exchange between the soil layer and the adjacent air. Based on typical vegetation used on green roofs in Mediterranean climates the properties described on Table 5 were assigned to the ecoroof model.

Height of plats [m]	0.2
Leaf Area Index [LAI]	3
Leaf Reflectivity	0.2
Leaf Emissivity	0.9
Minimum Stomatal Resistance [s/m]	180

Table 5. Input parameters of vegetation layer.

2.4.1.3 Additional green roof layers

In order to successfully add the soil and therefore the vegetation layer on the existing roof construction some protective and growth assisting layers are required to be laid right above the roof slab. The properties of these additional layers as introduced in the EnergyPlus (EERE 2013) model are described in Table 6.

Layers [outside-inside]	S [m]	λ [W/m K]	p [kg/m³]	c_p [J/kg K]
Filter layer	0.005	0.06	160	2500
Drainage layer	0.06	0.08	800	920
Waterproof layer	0.007	0.17	1200	920

Table 6. Thermo physical properties of additional green roof layers.

2.4.2 The Cool Roof

Based on the research of Akbari et al (2001), who have concluded that white is the most effective color for flat cool roofs, the ABOLIN COOL BARRIER ROOF WHITE is going to be used for the cool roof simulations. This product is available in the Greek market and listed in the European Cool Roofs Council Database (Fig.37) with a solar reflectance (SR) of 0.89. The material is going to be applied right above the existing terrazzo layer with the intervention of only a waterproof roof paper.

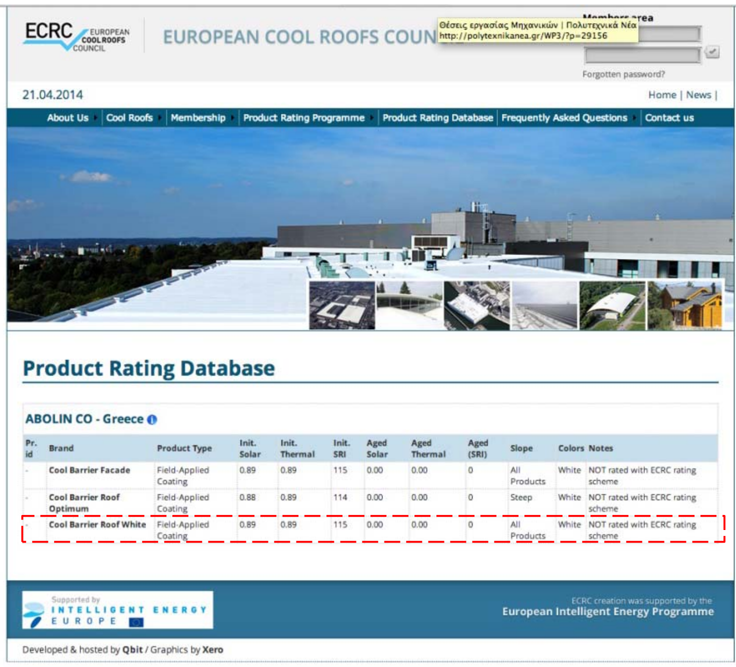

Figure 37. The ECRC Database for cool roof products available in Greece (ECRC 2014).

2.5 Zoning of the building

In order to more precisely simulate the internal conditions and energy loads of a building, it is necessary to divide it into zones with almost uniform internal conditions. Different zones are usually assigned to different spaces or group of spaces that have different occupancy, orientation and schedules. Zoning allows the user to adjust internal conditions by modifying thermostats, occupancy, lighting gain and infiltration or ventilation rate. In the case of the studied building each floor was separated into 3 zones and the entrance ground floor into one unheated zone.

As shown in Fig.38 on every floor the big family apartment is divided in two zones, the sleeping area in the North [NZ] and the living room and kitchen area in the South [SZ]. The studio apartment is considered as one zone with North orientation and the staircase and lift area is considered to be one unheated zone.

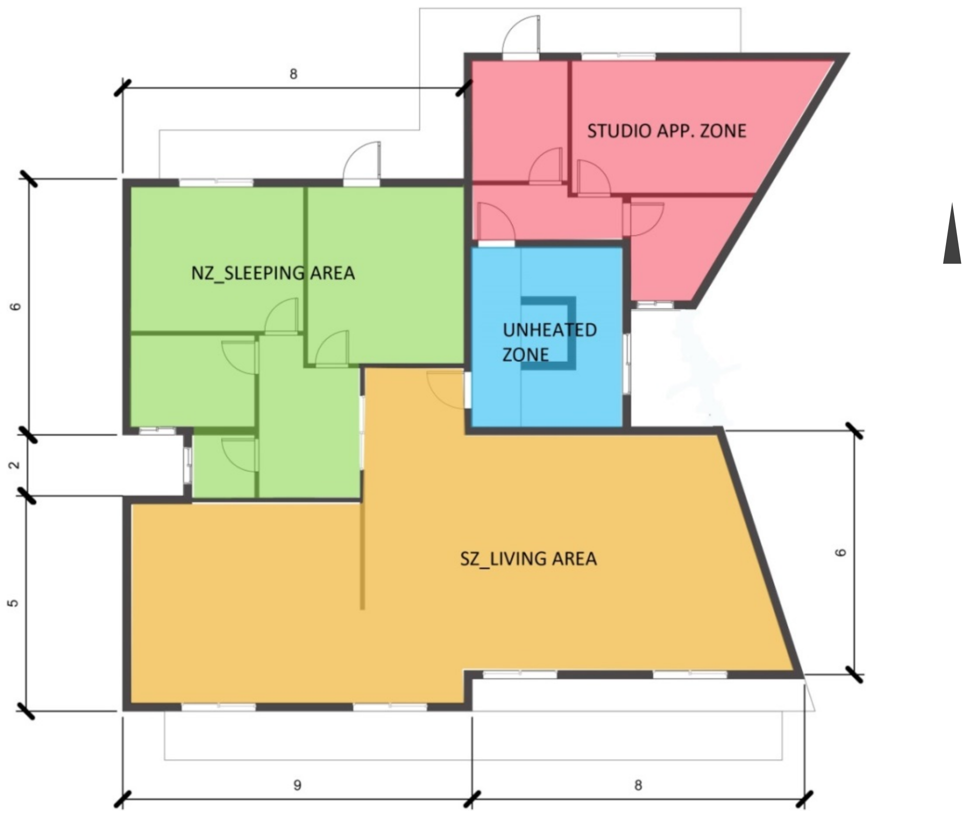

Figure 38. Floor zoning of the studied building.

Floor	Zone Name	Area [m²]	Volume [m³]
Ground Floor	UNCONDITIONED ENTRANCE	204.50	580.92
1st Floor	STUDIO APP1	53.08	159.23
	SLEEPING_N1	50.40	152.20
	LIVING_S1	100.02	300.06
	UNCONDITIONED STAIRCASE	14.80	44.4
2nd Floor	STUDIO APP2	53.08	159.23
	SLEEPING_N2	50.40	152.20
	LIVING_S2	100.02	300.06
	UNCONDITIONED STAIRCASE	14.80*	44.4
3rd Floor	STUDIO APP3	53.08	159.23
	SLEEPING_N3	50.40	152.20
	LIVING_S3	100.02	300.06
	UNCONDITIONED STAIRCASE	14.80*	44.4
4th Floor	STUDIO APP4	53.08	159.23
	UNCONDITIONED STAIRCASE	14.80*	44.4
TOTAL		881.86	2793.61

**The staircase zone area is considered only once in the total building area, as it is modeled as a shaft.*

Table 7. Building zones' area and volume.

2.6 Internal conditions and schedules

In order to more accurately simulate the existing building with its actual occupancy, assumptions were to be made regarding the heating, cooling, shading, infiltration, ventilation and internal gains of the zones. This input data can significantly affect the simulation results.

Two different series of simulations are conducted for each case of SR, GR and CR. The first series S1 is the free floating analysis, where no mechanical cooling or heating are available and is going to be conducted in order to obtain the inside temperature of the zones and compare the efficiency of the GR and the CR in providing thermal comfort. For the second series S2 the set-point temperature is assumed to be continuously maintained constant during specific hours of the day - when people are assumed to be active in the house - and heating and cooling system generators of unlimited power are implemented to keep these comfortable conditions. This assumption is going to lead to the overall assessment of the heating and cooling loads with the three different roof technologies SR, GR and CR (Fig.39).

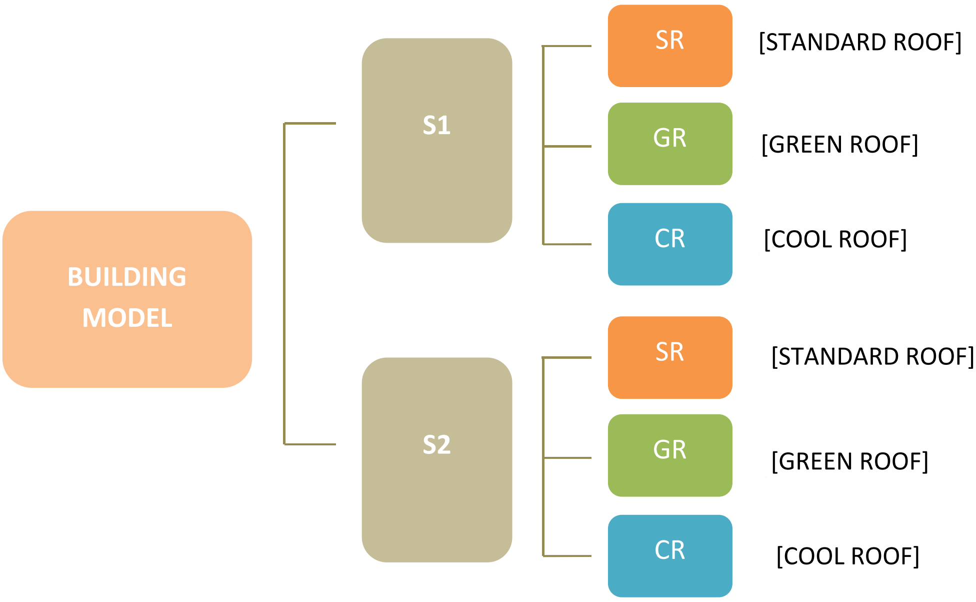

Figure 39. Hierarchy of the performed simulations, series S1 and S2.

In both simulation series some schedules and values remain constant, such as the operational schedule of the zones, the window blinds operation, the internal gains and the infiltration rate, while the thermostat set points and the natural ventilation rate differ for each case.

The occupancy for the family apartment divided in two zones is set to 4 people with a typical operational schedule for a residence throughout the whole year (Fig.40), while the studio apartment is considered to be occupied from 1 person (Fig.41). An average of gains defined at 80 W/person for the studio apartments, while at 70 W/m² for the sleeping zones and 100 W/m² for the living zones of the family apartments.

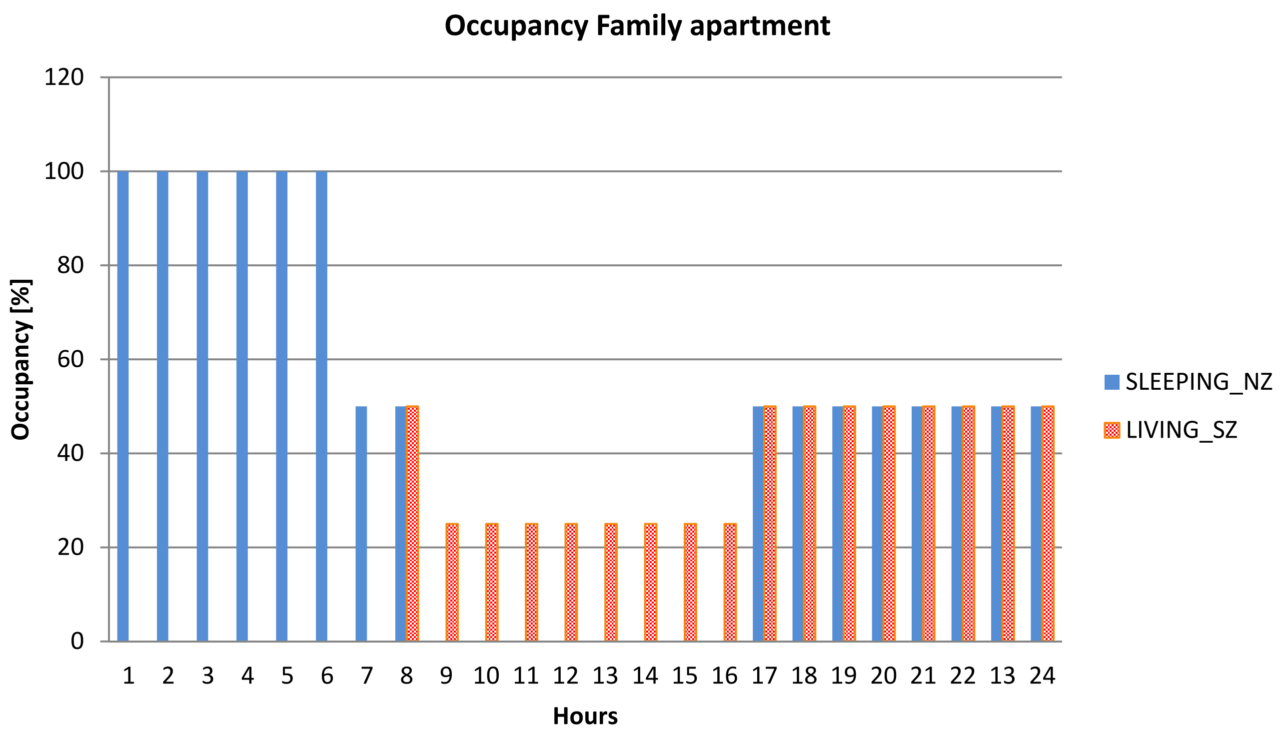

Figure 40. Occupancy schedule for the 2-zone apartment, S1 and S2.

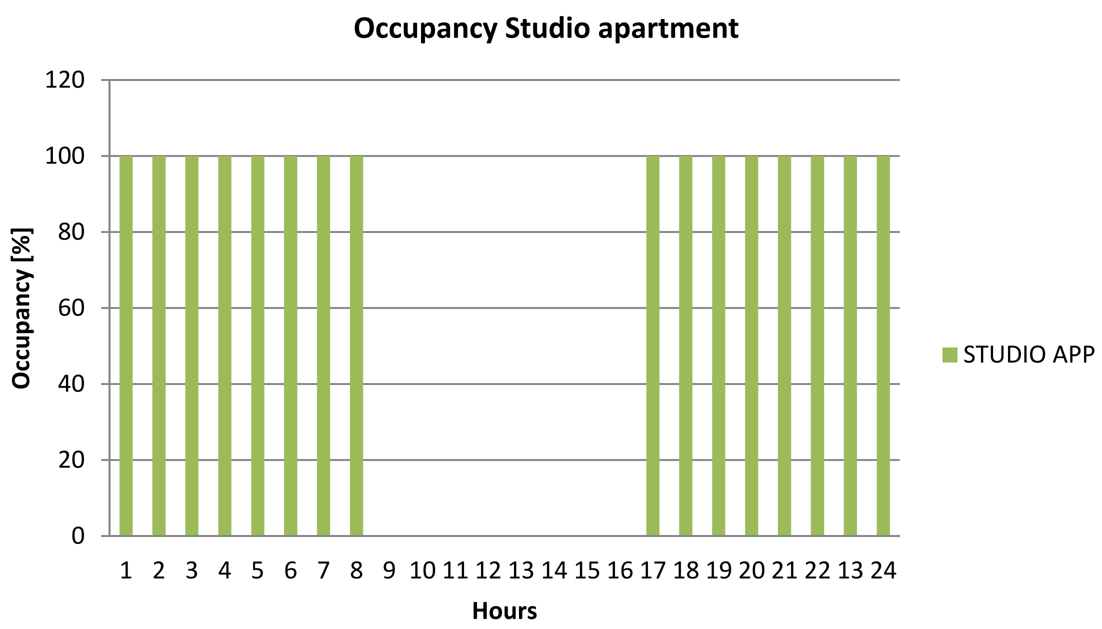

Figure 41. Occupancy schedule for the studio apartment, S1 and S2.

The infiltration rate for both series of simulations S1 and S2 is calculated based on the Greek regulation T.O.T.E.E. 20701-1 (p.82, Table 3.26), provided from the technical chamber of Greece. The total fenestration area for the conditioned part of the building is 102.82 m^2 and the air infiltration per window area, based on the regulation for double glazed door-windows with aluminum non insulated frame is set at 6.8 m^3/ (m^2h). Based on these values the total air infiltration for the conditioned zones of the building is 699.18 m^3/ h or **0.4 ach**.

The natural ventilation rate though is different for each one of the simulation series S1 and S2 and is set constant for the load analysis S2 at 0.5 ach, while a more realistic ventilation schedule is designed for the free floating analysis S1, based on the assumption that the natural ventilation increases during the summer nights in order to avoid overheating (Table 8).

NATURAL VENTILATION	S1		S2
	DAY 08:00-21:00	NIGHT 21:00-08:00	ALL DAY
Winter (October-April)	0.5 ach	0.5 ach	0.5 ach
Summer (May-September)	0.5 ach	3 ach	0.5 ach

Table 8. Natural ventilation schedule for the conditioned zones, S1 and S2.

The application of a schedule is also considered necessary for the manually operable window blinds, which are commonly used in the southern countries in order to regulate the sunlight entering the rooms. Based on a typical user the assumptions depicted on Table 9 are considered for both S1 and S2, with the blinds remaining open during the day and closed during the night in winter, while they remain open during the summer night allowing the increased natural ventilation rate mentioned on Table 8 and they are partially closed during the hot summer day in order to avoid overheating.

	DAY 08:00-20:00	NIGHT 20:00-08:00
Winter (October-April)	open	closed
Summer (May-September)	partially closed	open

Table 9. Window blind schedule for the conditioned zones, S1 and S2.

A schedule of operation and internal gains was also to be defined for the lighting equipment and the electrical appliances in the house and is valid for both simulation series S1 and S2. Based on the Greek Technical regulation T.O.T.E.E. 20701-1 (p.29, Table 2.4), provided from the technical chamber of Greece, the lighting levels for general domestic purposes are considered at 200 lx with a lighting power of 3.6 W/m² and the operational schedule follows the timelines described on Fig.42-43. The same procedure leads to the definition of the internal gains from electrical equipment at 2 W/m² and with an average operation fraction of 0.75 defined for the whole year and applied only in the living zone of the family apartment and the studio apartment.

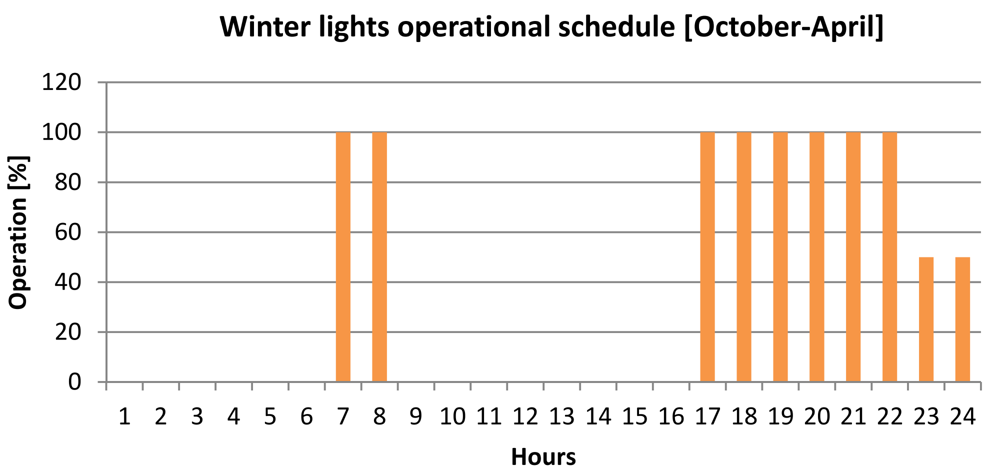

Figure 42. Lighting Operational schedule during winter, S1 and S2.

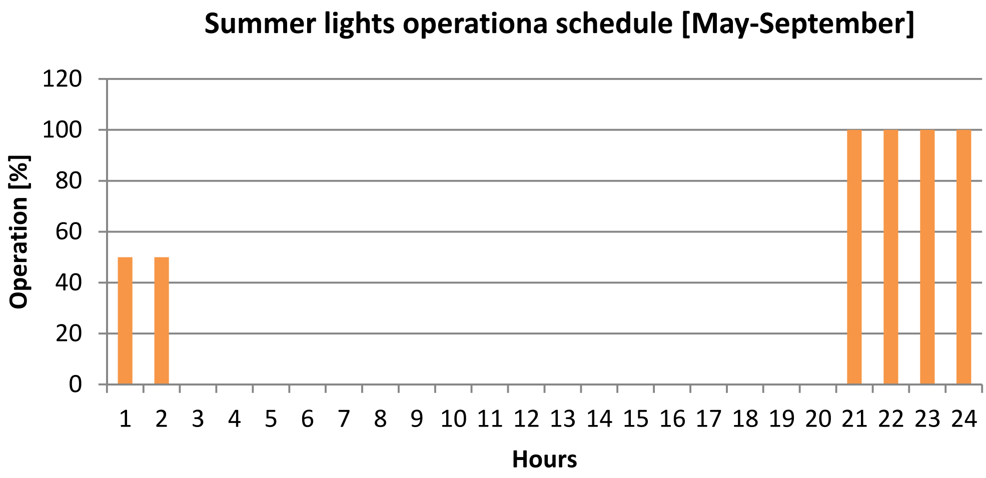

Figure 43. Lighting Operational schedule during summer, S1 and S2.

Last but not least, the thermostat set points throughout the whole year for both simulation series were to be defined, with deactivated HVAC system for the S1 and a constant comfort temperature preserved between 08:00-22:00 for S2 as shown on Table 10.

Value		S1		S2	
		CONDITIONED ZONE	UNCONDITIONED ZONE	CONDITIONED ZONE	UNCONDITIONED ZONE
Θih	°C	-100	-100	20	-100
Θic	°C	100	100	26	100

Θih = heating set point temperature

Θic = cooling set point temperature

Table 10. Cooling and Heating thermostat set points, S1 and S2.

3. Results and Analysis

3.1 Free floating analysis Indoor Temperature results

The first round of simulations was conducted using the S1 configurations described in Chapter 2. One simulation accounts for each roof construction variation SR, GR and CR. In total 3 free floating simulations were conducted (Fig.39) in order to obtain the data needed to assess the fluctuations of the indoor dry bulb temperature during the summer period. During the data analysis of S1 the attention is focused on the zones directly under the roof, which are also the most affected. More specifically the highest temperatures are reported in LIVING_S3, SLEEPING_N3 and STUDIO APP4 during the hottest day of the year on the midday of 6th of August as shown on Table 11.

6th August 15:00	OUTDOOR	LIVING ZONE_S3	SLEEPING ZONE_N3	STUDIO APP4
Dry Bulb Temperature ^{o}C	37	35	34	34

Table 11. Highest recorded Temperature for most affected thermal zones with existing roof SR.

Comparing the data output from all three cases SR, GR, CR for the 6th of August for the LIVING _S3, where the highest temperature is recorded, the temperature drop is obvious in both cases of roof refurbishment GR and CR, with the case of the green roof to be proven more efficient by achieving a temperature drop of 3^{o}C during midday and by maintaining this temperature difference throughout the day (Fig.44).

The effectiveness of both roof cases GR and CR is also obvious while analyzing the mean hourly indoor temperature data for LIVING _S3 during the two summer months with the highest overheating rate, July and August. These values are calculated by extracting the hourly data results for each day (T1,T2,..T62) of each month (July-August, 62 days total) and calculating the average of total 62 values for each hour using the formula (T1 + T2+…+T62) / 62.

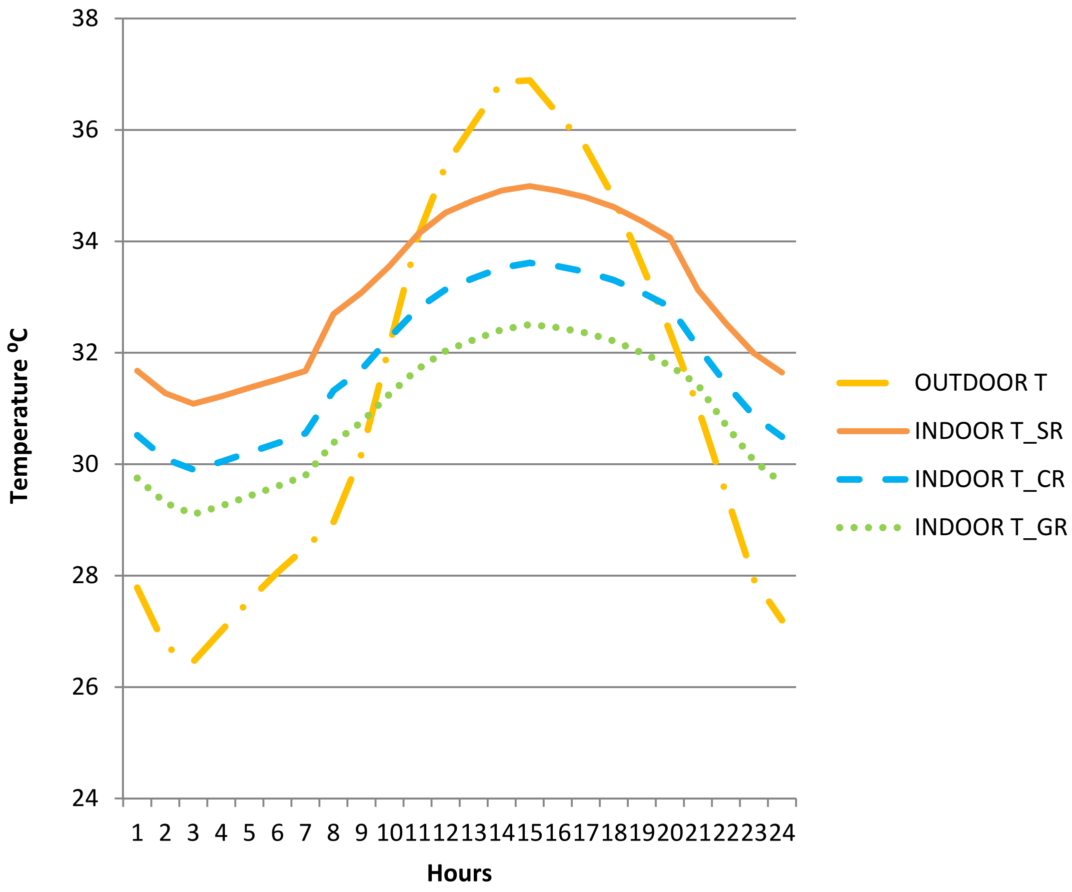

Figure 44. Temperature analysis for LIVING _S3 during August 6.

Once more the green roof technology is proven to be more effective with an average temperature drop of 3K compared to the SR and 1K compared to the CR throughout the day (Fig.45). It is also remarkable in both Fig. 41 and 42 and for all three roof cases that the indoor temperature remains remarkably high during nighttime compared to the environment dry bulb temperature, which drops 7-8 ^{o}C. This is the result of the bad thermal insulation and the high thermal mass of the brick walls, which result to stored heat and therefore high indoor temperatures during nighttime.

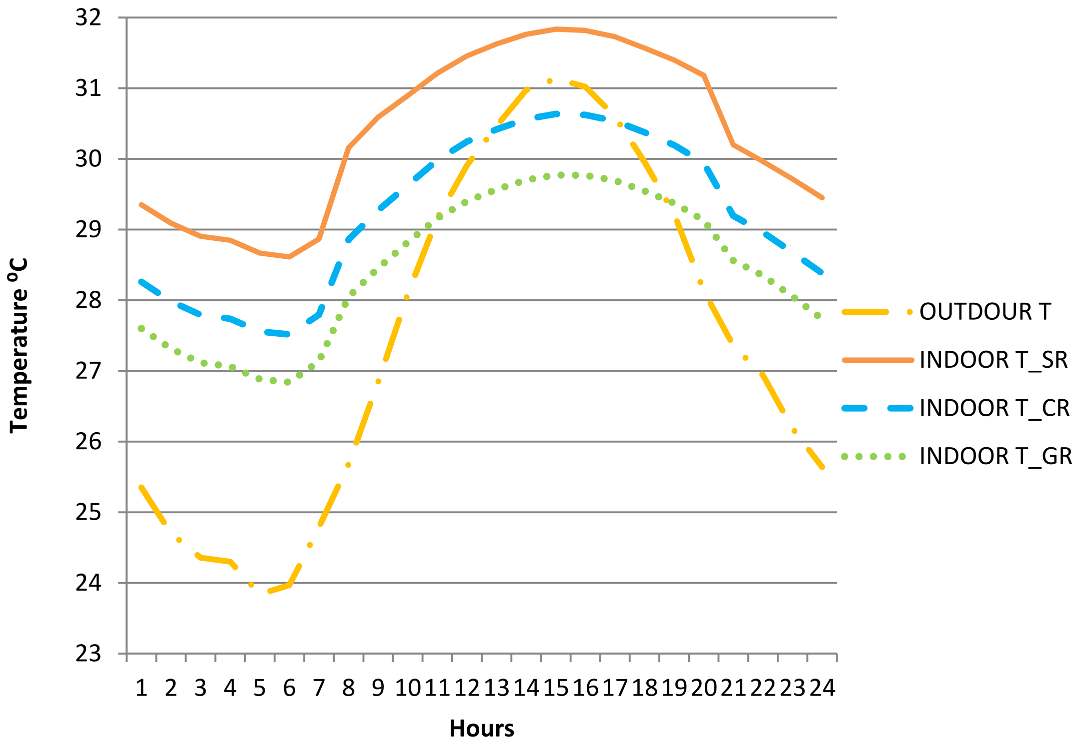

Figure 45. Mean Hourly Dry Bulb Temperature analysis for LIVING _S3, July-August.

Moving lower in the building on the second and first floor and observing the indoor mean temperature fluctuations (Fig.46-47) for the most affected south zones of each floor, it is obvious that the further down we move into the building the less effect there is by the replacement of the roof. The simulated indoor temperature changes between the different technologies are minimum, especially for the lowest occupied floor of the building. Furthermore, unlike the top floor, the temperature, during midday, does not exceed the outdoor temperature, even in the case of the standard roof, a fact that validates the great effect a flat roof can have on the thermal comfort of the spaces underneath it.

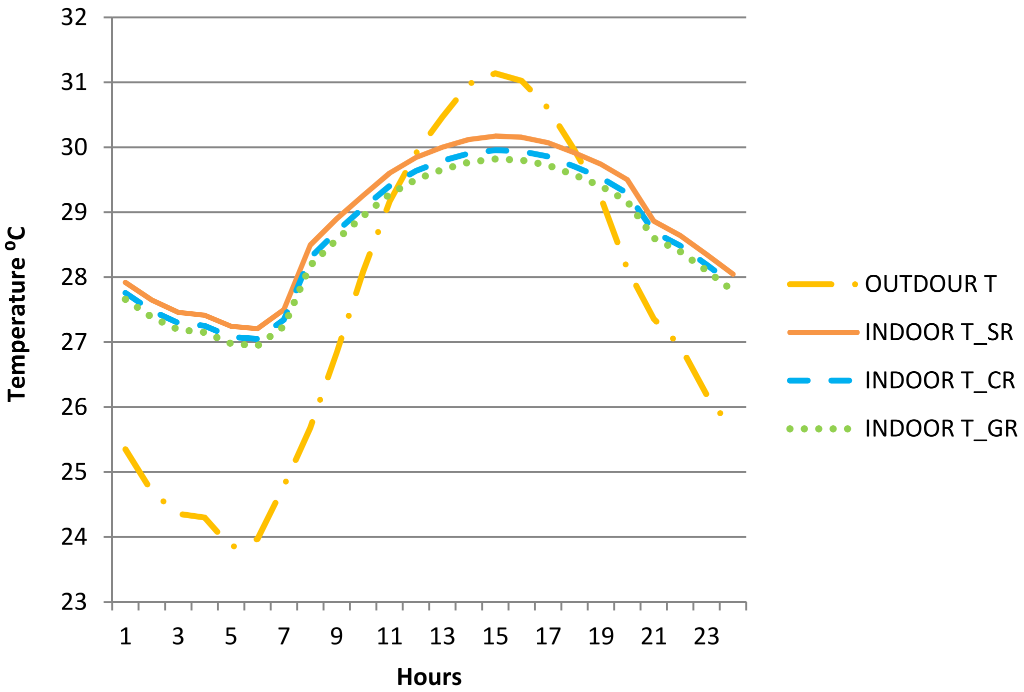

Figure 46. Mean Hourly Dry Bulb Temperature analysis for LIVING _S2, July-August.

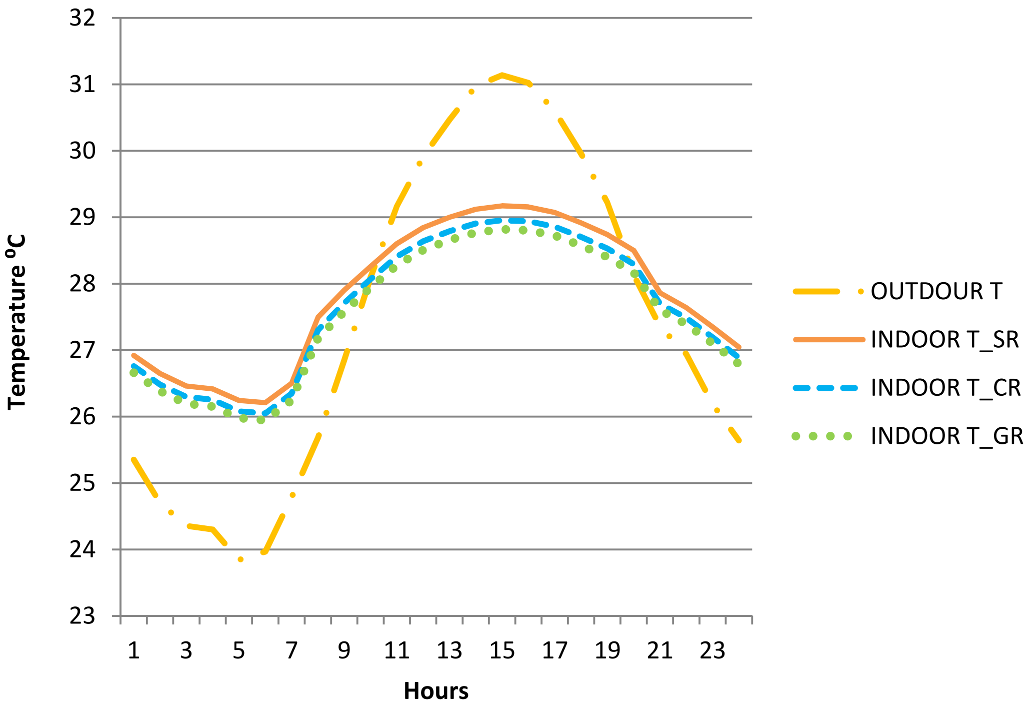

Figure 47. Mean Hourly Dry Bulb Temperature analysis for LIVING _S1, July-August.

Ultimately the efficiency of both roof variations GR and CR is validated through an overheating rate assessment during the period between June and September, which is the period of the year when the indoor dry bulb temperature rises above 26^{o}C. In order to assess the overheating rate during this period for the most affected zones of the building LIVING_S3, SLEEPING_N3 and STUDIO APP4 a cumulative frequency distribution is calculated for each zone by defining a temperature range of minimum 26 ^{o}C and maximum at 35^{o}C (Fig.48-50). As shown in Fig.48-50 in both cases GR and CR a decrease of the overheating hours is observed for all three most temperature sensitive zones with a difference of 15-25%. Once more the GR case is proven to present the lowest overheating rate with an approximate 25% drop compared to the SR.

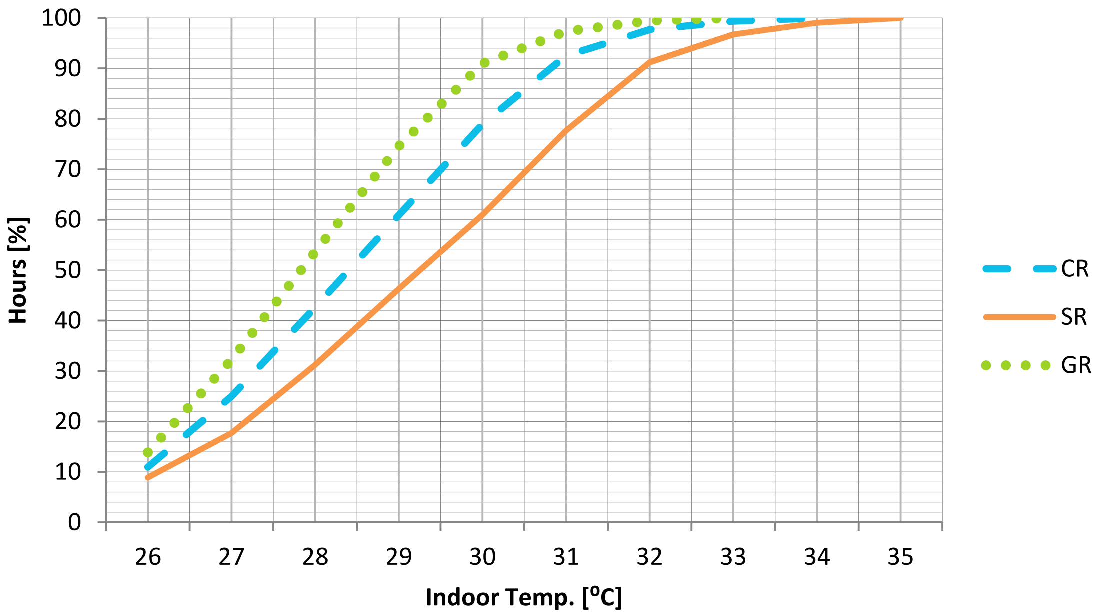

Figure 48. Indoor Temperature Distribution, June-September for LIVING_S3.

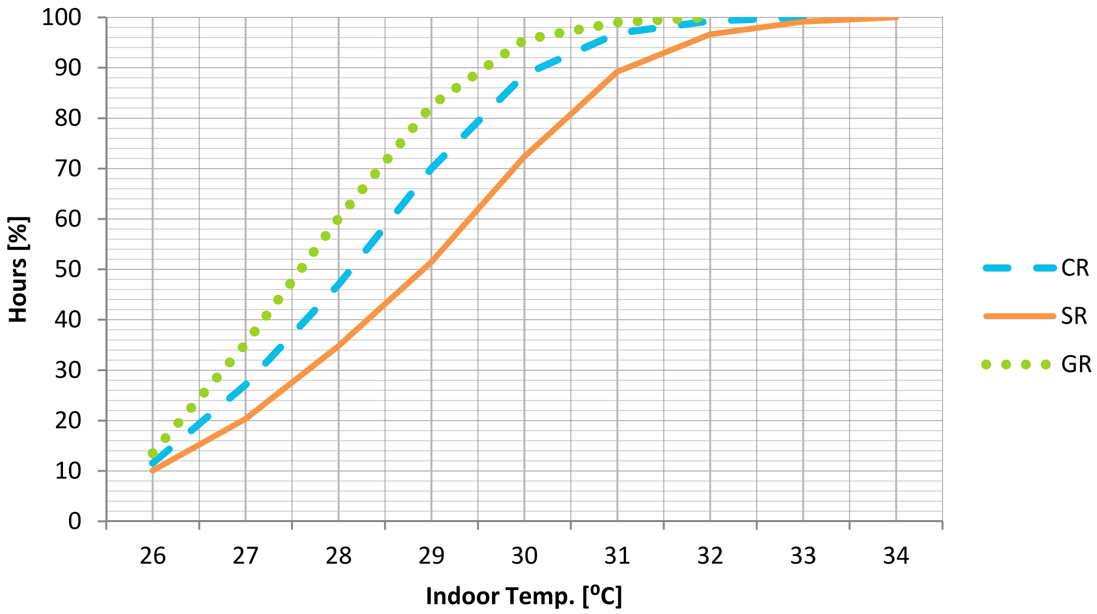

Figure 49. Indoor Temperature Distribution, June-September for SLEEPING_N3.

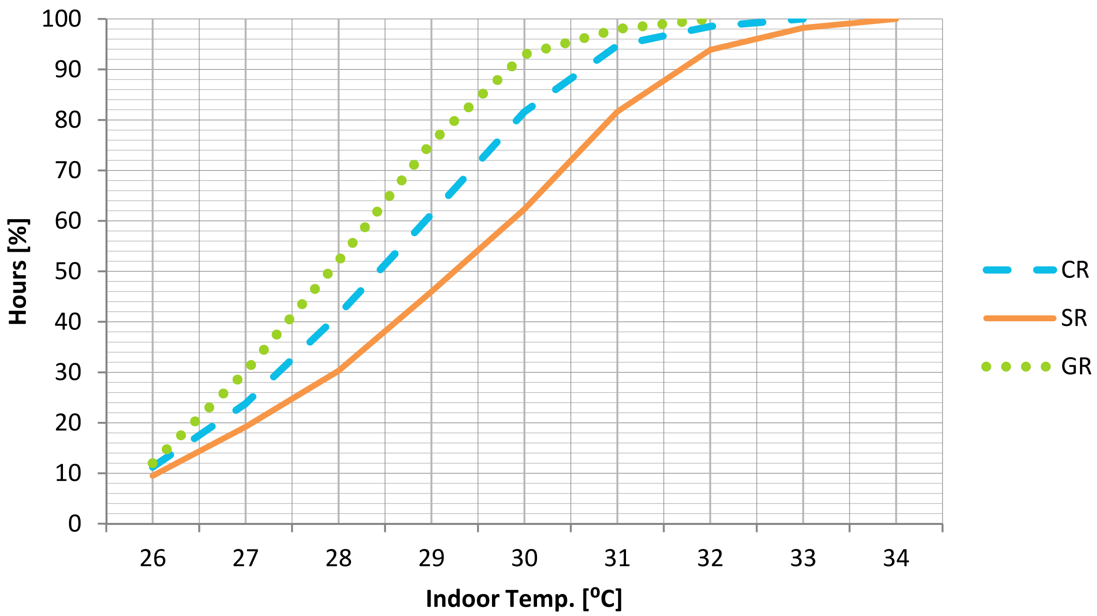

Figure 50. Indoor Temperature Distribution, June-September for STUDIO APP4.

OVERHEATING RATE (%)*									
FLOOR	SR			GR			CR		
	N_SLEEP	S_LIV	N_STUD	N_SLEEP	S_LIV	N_STU	N_SLEEP	S_LIV	N_STU
4	-	-	80.63	-	-	67.38	-	-	71.96
3	76.81	81.35	69.19	63.90	66.12	67.35	69.23	72.44	68.06
2	66.05	69.33	66.42	63.49	66.63	66.12	64.44	67.72	66.18
1	62.67	65.60	51.88	62.12	65.09	51.74	62.29	65.33	51.77

**percentage of hours when indoor T >26°C*

Table 12. Overheating rate for every simulated zone.*

Calculating and comparing the overheating rate for all other zones on the 3rd, 2nd and the 1st floor, that are not situated directly underneath the flat roof (Table 12, Fig.51-52), by dividing the number of hours with recorded temperature above 26 °C to the total number of hours of the given period and multiplied by 100, (ΣhT>26/Σh) x 100, it is once more obvious that while the roof can play a major role in formulating the indoor conditions of the top floor zones, it can hardly affect the temperature of the zones on the lower levels. The reduction of the overheating rate reaches an average of 2% for the 2nd floor zones, while it drops to a minimum 0.3% for the 1st floor zones (Table 12).

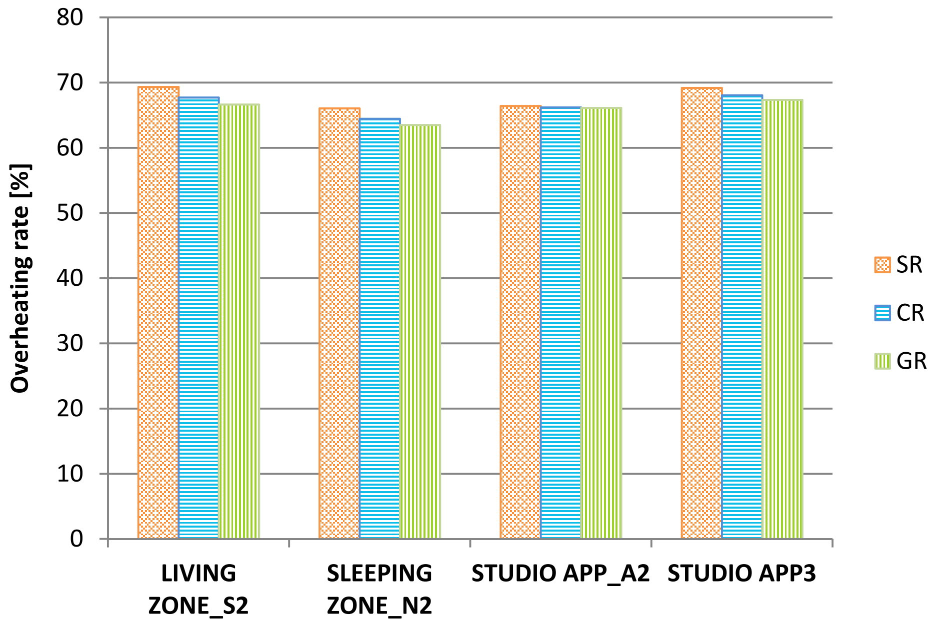

Figure 51. Overheating Rate June-September for 3rd and 2nd floor zones situated underneath other occupied zones.

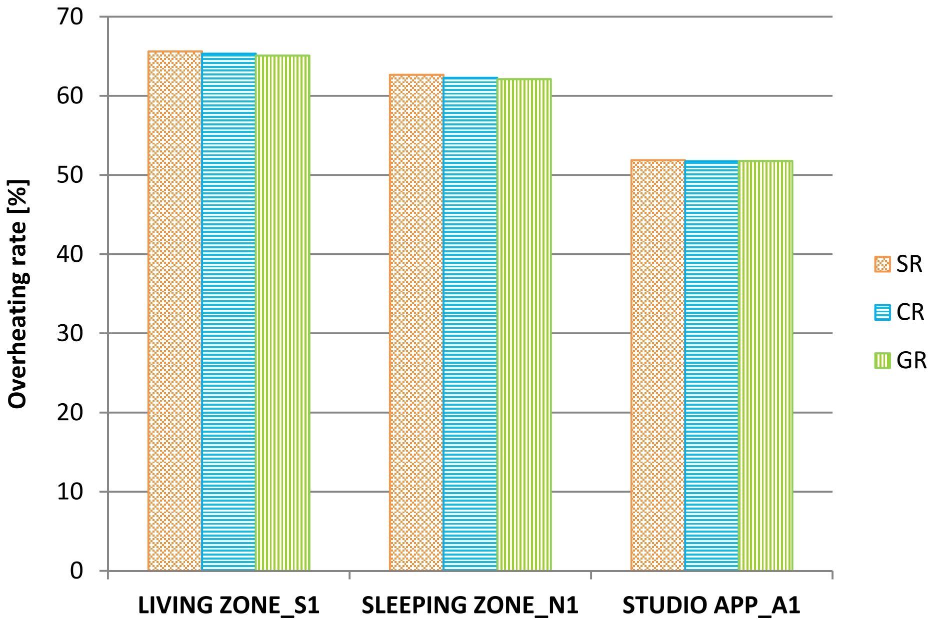

Figure 52. Overheating Rate June-September for 1st floor

3.2 Comparison of Cooling and Heating Loads

After using the configurations described in Chapter 2 for the S2 simulation series**,** the three different simulations were performed for the three different roof configurations SR, GR, CR.
From the summary of the results regarding the annual cooling and heating loads per m² for each zone, presented in Table 13-14, it is obvious that the lower we move in the building the less affected are the results from the roof refurbishment in both of the cases.

ANNUAL COOLING LOADS ($KWhm^{-2}a^{-1}$)									
FLOOR	SR			GR			CR		
	N_SLEEP	S_LIV	N_STU	N_SLEEP	S_LIV	N_STU	N_SLEEP	S_LIV	N_STU
4	-	-	48.87	-	-	24.82	-	-	33.16
3	42.94	45.73	24.31	22.21	22.66	22.91	29.54	30.65	23.33
2	21.42	22.92	22.24	20.17	21.24	22.07	20.55	21.78	22.12
1	19.62	20.71	15.29	19.45	20.56	15.23	19.49	20.58	15.28
MEAN	**28.40**			**21.13**			**23.64**		

Table 13. Annual cooling loads for every simulated zone.

ANNUAL HEATING LOADS (KWh$m^{-2}a^{-1}$)									
FLOOR	**SR**			**GR**			**CR**		
	N_SLEEP	**S_LIV**	**N_STU**	**N_SLEEP**	**S_LIV**	**N_STU**	**N_SLEEP**	**S_LIV**	**N_STU**
4	-	-	60.35	-	-	50.94	-	-	57.96
3	63.70	52.58	44.85	54.31	44.68	44.85	61.37	50.74	44.59
2	47.49	38.53	44.15	47.07	38.13	44.04	47.19	38.31	43.86
1	44.98	32.27	44.05	44.96	37.05	43.75	44.71	37.25	43.78
MEAN	**47.30**			**44.97**			**46.97**		

Table 14. Annual heating loads for every simulated zone.

Initially focusing on the total Cooling and heating Energy of the whole building the results show a 24% drop in the cooling loads in the case of the green roof, while a 16% decrease accounts for the cool roof. Both roof configurations perform better during the summer period compared to the winter period, with the green roof performing significantly better than the cool coating even during the winter, when, as expected, there is barely any reduction in the heating loads resulting from the white coating application (Fig.53).

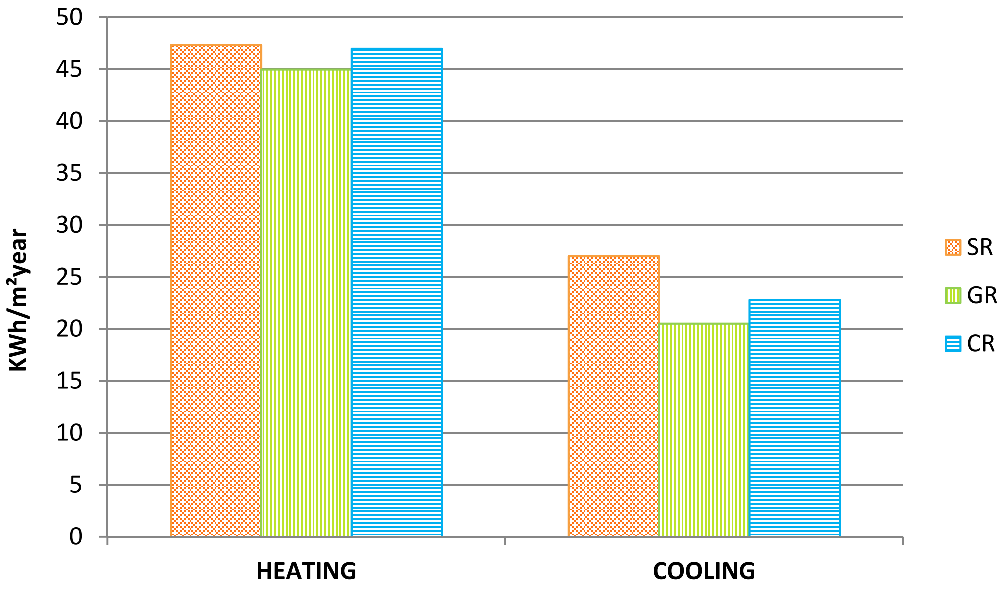

Figure 53. Annual Heating and Cooling loads per m² of the whole building.

At this point of the results' analysis it is considered significant to focus once more on the apartments directly under the roof element and compare the effect of the roof replacement for every floor.

Focusing on the zones LIVING_S3 and SLEEPING_N3 of the family apartment on the 3rd floor and on the one-zone studio apartment STUDIO_APP4 on the 4th floor the building, the resulting energy reduction for heating and especially for cooling is much more remarkable (Fig. 54- 56). A 50% drop in the cooling load for the South Zone of the family apartment and a 48% and 49% cooling energy decrease for the North Zone and the Studio Apartment respectively is observed with the application of the green roof, while the cooling loads drop 31% and 32% respectively with the application of the cool roof coating. Although the effects of both roof technologies are proven to be effective in reducing the cooling loads, no significant decrease of the heating loads is observed in the case of the green roof (9-15%) and a minimal drop of about 2-4% is the result of the cool roof coating.

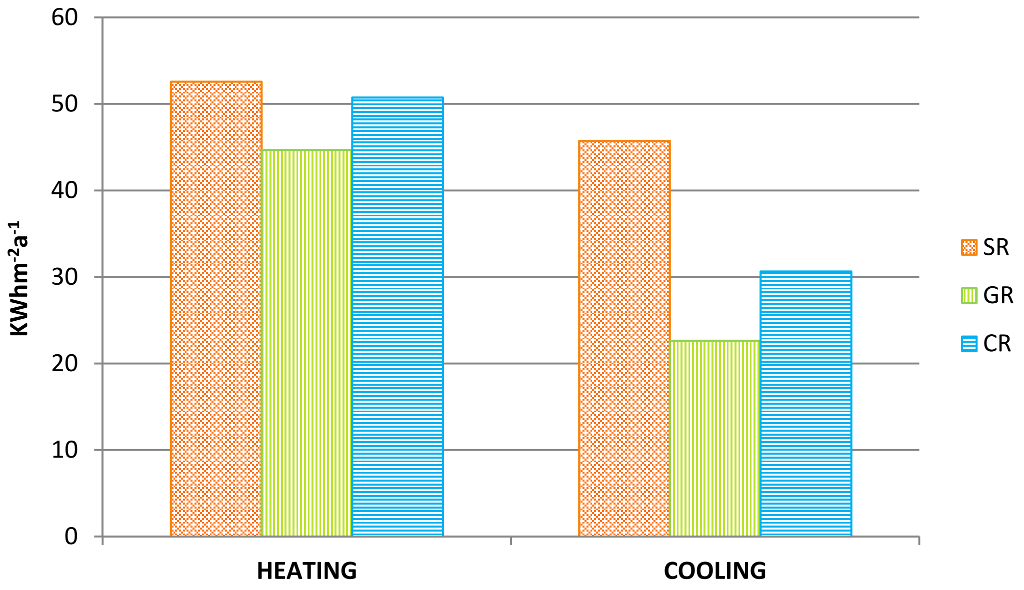

Figure 54. Annual Heating and Cooling loads per m² LIVING_S3.

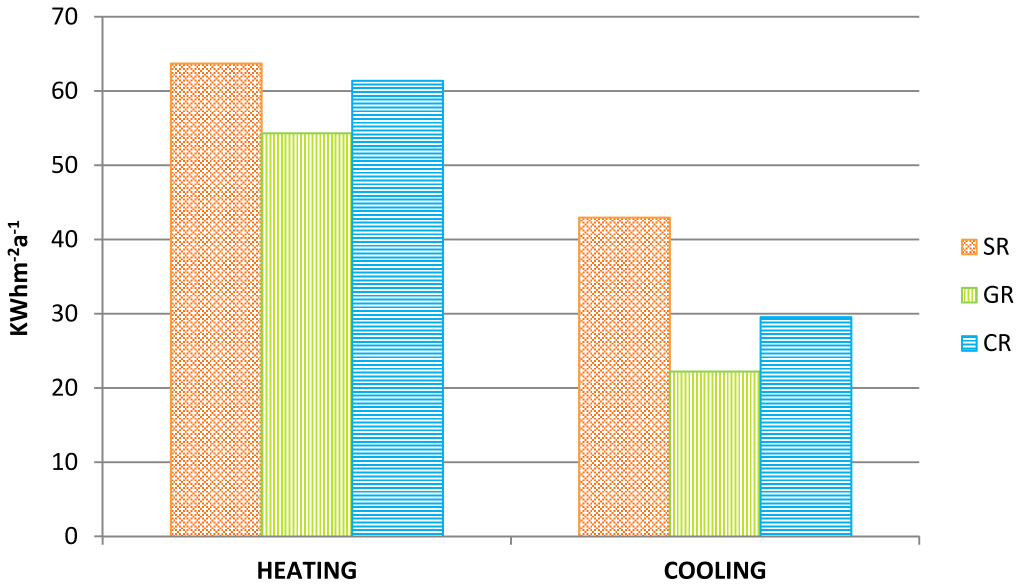

Figure 55. Annual Heating and Cooling loads per m² SLEEPING_N3.

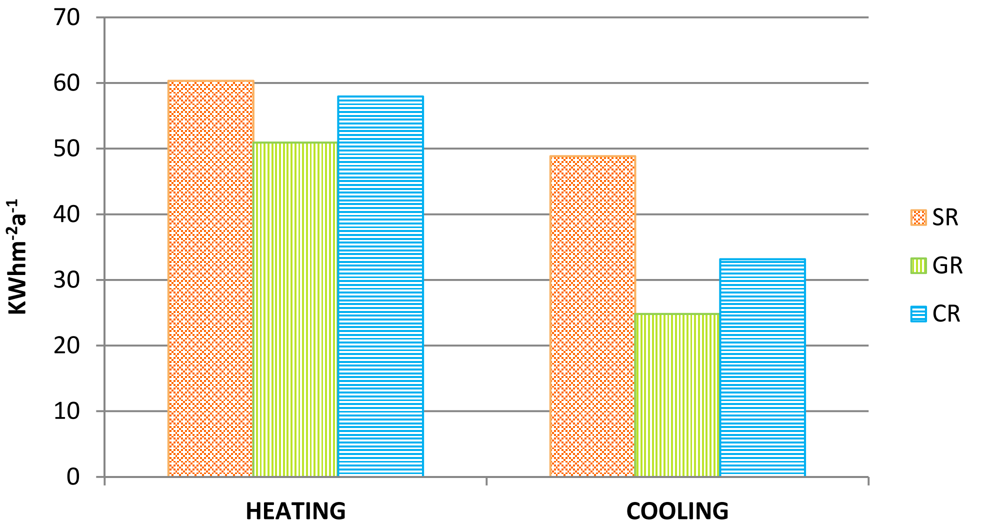

Figure 56. Annual Heating and Cooling loads per m² STUDIO APP 4.

Moving lower in the building and comparing the cooling loads of the top floor apartments to those right underneath (Fig.57, Table 13), we can see that the reduction is not equivalent. It is obvious that the refurbishment of the roof with either of the two technologies affects mostly the top floors and its effect fades away while moving towards the lower floors.

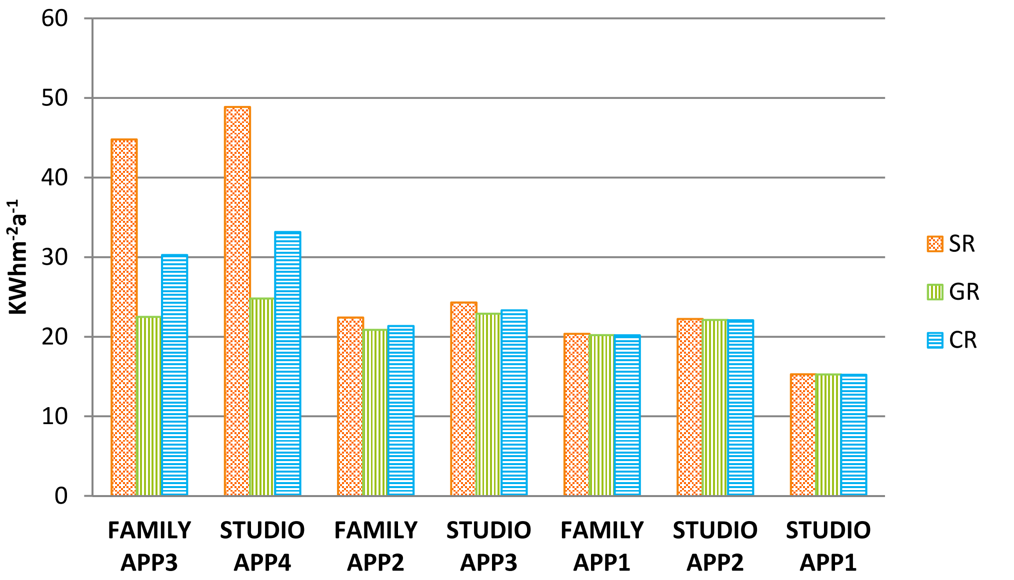

Figure 57. Annual Cooling loads per m² for each apartment.

4. Conclusion

4.1 Conclusions

This work is an attempt to validate the positive effect of the roof refurbishment on a building's thermal behavior, while simultaneously comparing two of the most popular roof cooling techniques. This positive contribution is more obvious during the summer period, which is the most critical period in terms of energy consumption and environmental footprint for Southern European countries such as Greece.

Both technologies have shown great potential as a sustainable way to enhance a building's thermal performance and at the same time contribute to the improvement of the microclimate in urban environments. Green roofs have proven to bring slightly better results than white cool roofs, in lowering significantly the cooling loads up to 50% and at the same time affecting positively the behavior of the building envelope also during the winter, with a heating load reduction up to 15%. However these positive effects on the building are mainly limited to the upper storey. Calculating and comparing the overheating rate for all floors, as well as the cooling loads using both roof alternatives, has led to the conclusion that while the roof can play a major role in formulating the indoor conditions of the top floor zones by decreasing the amount of overheating hours up to 30%, it can hardly affect the temperature of the zones on the lower levels. These results lead to the assumption that in tall buildings the total energy conservation due to roof refurbishment can be limited to minimum, depending on the number of floors.

Moving forward and assessing the procedure of the simulations, modeling and simulating the green roof element has proven to be a more complicated task, with a lot of parameters and highly dependable from regional and climatic data. This argument is also supported by various studies on green roofs which focus most of the time on one element of the green roof (vegetation, soil, drainage layer etc.) and its properties, or even one climatic region. The same does not apply for cool roofs, which have recorded and listed properties, a fact that makes them easy to simulate while the limited layers allow for more steady and comparable results even in different climates and geographical locations.

The development of more user-friendly green roof simulation modules incorporated into modern whole-building simulation models can play a major role in growing more awareness among engineers and designers. The cool roof initiative, on the other hand, is much more popular and well promoted among the southern European countries.

However, the target should be to produce a more comprehensive and long-term effect in a community or even a city, rather than individual investments which bring results in building level only. Much attention and resources should be focused on the retrofit of low insulated existing constructions, which are a huge part of the urban context, and the roof refurbishment is the least invasive and more cost effective way to achieve that.

4.2 Future Research

Throughout this study it was clearly obvious that the green roof technology is the least analyzed technology in comparison to the cool roof coatings, which are more efficiently promoted and thoroughly studied. Most of the reported field measurements and simulation studies on green roofs have been conducted only during the past few years, a fact that shows that the study of green roofs is an ongoing procedure that will include more information in the future. However, since most of the available research focuses on the effect of green roofs during summer periods, maybe a more comprehensive study on the performance of green roofs during winter in different climate zones could also be enlightening.

It would also be interesting to conduct a comparative analysis between the two passive cooling techniques studied here with other environmentally friendly insulation solutions that could possibly be applied on a roof, and how they react in different climates. However, it would be even more interesting to move even further than the thermal behavior comparison and investigate deeper the environmental impact of these materials on a broader level. It is really time to overcome individuality and to start think globally and past our energy costs, in order to move further in creating more pleasant urban environments and therefore contribute to the global cooling potential.

5. List of Figures

6. List of Tables

7. References

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