Cyprus University of Technology

Faculty of Geotechnical Sciences and Environmental Management

Doctoral Dissertation

Urban Energy and Environmental Modelling: The case of green roofs

Isidoros Ziogou

Limassol, February 2023

CYPRUS UNIVERSITY OF TECHNOLOGY

FACULTY OF GEOTECHNICAL SCIENCES AND ENVIRONMENTAL MANAGEMENT

DEPARTMENT OF CHEMICAL ENGINEERING

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Supervisor: Alexandros Charalambides, Associate Professor, Department of Chemical Engineering, Cyprus University of Technology

Signature ____

Member of the committee: Stylianos Yiatros, Associate Professor, Department of Civil Engineering and Geomatics, Cyprus University of Technology

Signature ____

Member of the committee: Symeon Christodoulou, Professor, Department of Civil and Environmental Engineering, University of Cyprus

Signature ____

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ABSTRACT

The objective of this doctoral research is to explore green roofs, as a nature-based solution, for improving the sustainability in urban areas of various climatic characteristics and different geometrical formations, with a focus on residential and office buildings. The appropriateness of these options has been assessed with the aid of energy, environmental and economic modelling. The results of this study indicatively demonstrate energy savings in individual buildings than can reach up to 35%, emission reductions of 3-10 tons of CO_2, 2-6 kg of NO_x and 7-18 kg of SO_2 per building per year, good economic prospects for individual users, with only modest reductions (varying from 6% to 35%) in green roofs' installation cost and, finally, reduction of urban air temperature reaching up to 0.35 K. Especially when it comes to city-level upgrades, green roofs can be either an immediate or a long-term measure for sustainable urban development. This potential should be an additional incentive for the responsible statutory and administrative bodies to adopt policies that economically promote the design and implementation of urban green roof retrofitting projects.

Keywords: green roofs, economic evaluation, energy efficiency, environmental upgrade, urban neighborhood.

ΠΕΡΙΛΗΨΗ

Η διδακτορική αυτή διατριβή διερευνά την εφαρμογή της τεχνολογίας των πράσινων οροφών, ως λύση βασισμένη στη φύση, για τη βελτίωση της βιωσιμότητας στις αστικές περιοχές με διαφορετικά κλιματικά και γεωμετρικά χαρακτηριστικά, με έμφαση στα κτίρια κατοικιών και γραφείων. Η καταλληλότητα των εναλλακτικών επιλογών έχει αξιολογηθεί με τη βοήθεια ενεργειακής, περιβαλλοντικής και οικονομικής μοντελοποίησης. Τα αποτελέσματα αυτής της μελέτης καταδεικνύουν κυρίως την εξοικονόμηση ενέργειας σε μεμονωμένα κτίρια που μπορεί να φτάσει έως και 35%, μειώσεις εκπομπών κατά 3-10 τόνους $CO2$, 2-6 kg NOx και 7-18 kg $SO2$ ανά κτίριο ανά έτος, καλές οικονομικές προοπτικές για εφαρμογή από μεμονωμένους χρήστες, μετά την εφαρμογή συντηρητικών μειώσεων κυμαινόμενων από 6% έως 35% του αρχικού κόστους εγκατάστασης και, τέλος, βελτίωση της θερμικής άνεσης μέσα στο αστικό περιβάλλον, με την μείωση της θερμοκρασίας στο ύψος ενός πεζού, να κυμαίνεται στους 0,35 K. Ειδικά όταν πρόκειται για συστηματική και ευρεία εφαρμογή των πράσινων οροφών σε επίπεδο πόλης, η συγκεκριμένη λύση φαίνεται να μπορεί να αποτελέσει ένα μακροπρόθεσμο μέτρο άμεσης και έμμεσης περιβαλλοντικής αναβάθμισης. Αυτή η δυνατότητα θα πρέπει να αποτελέσει ένα πρόσθετο κίνητρο για τους αρμόδιους φορείς να υιοθετήσουν πολιτικές που προάγουν το σχεδιασμό και την υλοποίηση έργων πράσινων οροφών σε κτίρια των αστικών κέντρων.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

This doctoral research explores technological solutions suitable for enhancing urban sustainability, with buildings being in the center of attention. For the suitability of these solutions to be evaluated, energy, environmental and economic modelling has been utilized.

Recent developments in environmental awareness, promoted by robust scientific research results and incorporated in the reports and outlooks of relative international (IPCC, 2014) and European (EEA, 2017) organizations, along with intensive urbanization trends (United Nations-Department of Economic and Social Affairs-Population Division, 2015), and technological advancements in the field of renewable energy (Rigter, Saygin and Kieffer, 2016) and raw materials (UNEP, 2014) show a clear path towards the necessity of reconsidering the way we build and manage contemporary cities.

This trend has been comprehensively examined under the scheme of Smart (and) Sustainable Cities, through interdisciplinary and transdisciplinary scientific research and corporate practice (Batty *et al.*, 2012). Generally, there is still a difficulty in coming up with a broad and standardized determination of this term (especially the "smart" part), since on the one hand it has been applied to infrastructure and buildings and on the other hand it has been related to intangible elements of cities like policy making and education (Albino, Berardi and Dangelico, 2015; Ahvenniemi *et al.*, 2017). Nevertheless, a quite coherent definition of a smart sustainable city is the following: "…meets the needs of its present inhabitants without compromising the ability for other people or future generations to meet their needs, and thus, does not exceed local or planetary environmental limitations, and where this is supported by ICT", serving both intragenerational and intergenerational justice (Hilty and Aebischer, 2015).

1.1 Literature review

In the aforementioned field, one of the main aspects that is under consideration and constant effort of improvement is the so-called urban metabolism, which can be defined as the process of different inputs (water, energy, food, materials) by building and infrastructure operations, human physical activities and transportation and the generation of outputs in the form of waste (Newman, 1999; Codoban and Kennedy, 2008; UNEP, 2013). Urban metabolism's upgrade can be accomplished by either improving the synergies between dwellers and infrastructure (including buildings) in the existing urban formations, or by intervening in the energy efficiency and technological devices of newly established urban formations (Rassia and Pardalos, 2015). These actions can ultimately lead to resilient urban systems against different types of hazards, trends and threats imposed by environmental degradation and climate change, economic crises, societal instabilities, and energy challenges (Rassia and Pardalos, 2014) and provide cities and citizens with the necessary balance between the natural environment and human development (Neuman, 2005).

Resilience, inclusiveness, safety and sustainability of cities and human settlements in general, as these are defined in the recent UN report regarding the 17 established sustainable development goals (UN, 2017), can be achieved if effort is put in the often interconnected sectors of economy, people, governance, mobility, living and environment. Among their many characteristics are: entrepreneurship and economic productivity, level of qualification and creativity, participation in decision-making and transparent governance, local accessibility and sustainable, innovative and safe transport systems, social cohesion and housing quality, and environmental protection and sustainable resource management (Giffinger *et al.*, 2007). These measures of performance actually constitute a measure of “smartness” and sustainability of cities.

Two prevailing sustainable urban forms that are widely examined for their positive triple contribution towards economic upgrade, social development and environmental improvement are “compact city” and “eco-city” (Jabareen, 2006). The former is strongly characterized by high density, diversity and mixed-land use. The latter gives priority to ecological design, passive solar design, and urban greening. With the attention focused on the built environment, the primary method of achieving the preferable sustainable urban (trans-) formations is through appropriate procedures of planning and design (Bibri and Krogstie, 2017). Urban planning refers to the arrangement of a city’s tangible elements (buildings, infrastructure, etc.) in a way that tends to maximize the cities’ desirable features of livability and attractiveness. Urban design as an interdisciplinary scientific area entails the architecture and civil engineering interventions starting from individual buildings to neighborhood scale implementation and ultimately to district- and city-level improvements.

Taking into account the upward trajectory that global energy demand is following and given the significant share of the energy consumption by the building sector, one should consider this sector carefully and often independently from other relating ones (Berardi, 2017). Directive 2010/31/EU on the energy performance of buildings (EPBD) has been developed in order to promote the improvement of the energy performance of buildings within the European Union, taking under consideration several influencing factors and introducing minimum requirements regarding both new and existing buildings (EU. European Union, 2010). This ambitious target can be achieved by nearly zero-energy buildings that according to the EPBD are the buildings that have "a very high energy performance, on the basis of the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs to maintain the envisaged temperature conditions of the building, and domestic hot water needs. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby."

Some of the utilized technologies in ZEBs which are integral parts of smart cities (Kylili and Fokaides, 2015; Riffat, Powell and Aydin, 2016) are photovoltaics (PV) and building integrated photovoltaics (BIPV) that are included in the renewable energy generation technology; green roof technology, a nature-based solution which compensates for the greenfield sites possibly occupied by city planning extensions or constructions of new settlements and constitutes an element of passive design techniques (Cao, Dai and Liu, 2016); and photovoltaic-green roofs (Chemisana and Lamnatou, 2014; Lamnatou and Chemisana, 2015).

Green roofs have been in the center of research for several years, mainly due to their positive contribution towards energy savings of individual buildings and thermal comfort enhancement of the occupants. Lately, effort is given into the quantification and economic evaluation of the benefits associated with the systematic and spatially expanded application of this passive energy efficiency measure of buildings, in terms of air quality upgrade and improvement of the urban thermal climate. This tendency is highlighted through a growing body of literature. Integration of green roofs into the urban context, through public or private investments, has exhibited increasing acceptance, because of reductions in energy consumption of individual buildings and the amelioration of the microclimatic conditions of the broader area (Akbari and Kolokotsa, 2016).

Green roofs offer many positive services among which lie urban heat island (UHI) mitigation, increased thermal comfort for building occupants and important energy savings (Saadatian *et al.*, 2013). More specifically, heat fluxes from the building roofs can decrease by roughly 80% in summer, while reduction in energy consumption during the same time period can reach almost 17%, compared with conventional roofs. A noteworthy temperature difference of the order of 4 °C between traditional and vegetated roofs can also be spotted in winter (Besir and Cuce, 2018).

Various experimental approaches have been employed so far attempting to evaluate the thermal and energy performance of green roofs. Bevilacqua et al., (2016) found that under common Mediterranean climatic condition and in comparison with conventional roofing options, thermal energy entering from the building's green roof can be eliminated during summer, while the corresponding energy flowing outwards in winter can be reduced up to 37%. In Shanghai, a coastal city with hot and humid summers, the cooling effect of green roofs is more profound on sunny days, with the largest difference in heat flows through the roof reaching 15 W/m^2 (He *et al.*, 2016). In cold climates, like the one prevailing in West Lafayette, Indiana, the examined retrofit option can cut down the heat loss of the inner roof area by almost 18% during the whole heating period, compared to the conventional structure (Tang and Qu, 2016). Green roofs also present higher temperature than white gravel roofs in regions with temperate climates, where heating is more important than cooling (Taleghani *et al.*, 2014).

Recent studies have confirmed that the main factors that influence the energy efficiency of a green roof are the height of the selected vegetation, the leaf area index (LAI), the minimum stomatal resistance, and the growing medium's depth (Refahi and Talkhabi, 2015; Costanzo, Evola and Marletta, 2016; Silva, Gomes and Silva, 2016). Berardi (Berardi, 2016) found that the examined building energy consumption is more intensively affected by the soil height than the LAI of the green roof, while the latter characteristic's magnitude is proportional to the cooling effect on local microclimate of urban areas. The last aspect is of great importance, especially if someone considers that UHI effect is directly linked with the energy consumption in cities. For example, the effect of the summer UHI alone raised the air-conditioning load up to 12% in Manchester, UK (Skelhorn, Levermore and Lindley, 2016a). Green roofs coupled with vegetation at pedestrian level positively affect urban microclimate (Alcazar, Olivieri and Neila, 2016), with urban planning conditions, design configuration and prevailing local climatic characteristics being basic factors in the overall performance (Morakinyo *et al.*, 2017).

In absolute terms, M. Santamouris (Santamouris, 2014), after comprehensively reviewing cities' cooling techniques through a wide range of numerical studies, highlighted that green roofs can decrease the mean air temperature in urban canyons between 0.3 and 3 K. A similar reduction of the order of 0.35 K in ambient air temperature was observed in the simulation results regarding neighborhood-scale implementation of green roofs at a typical warm Mediterranean region (Ziogou *et al.*, 2018). Substantial difference is also noticed in human thermal comfort values, where the Universal Thermal Comfort Index reduction in absolute terms can reach 1.5 °C and 5.7 °C, at pedestrian and roof surface height, respectively (Imran *et al.*, 2018).

Moreover, in an attempt to give prominence to the interconnection between increased urban air temperatures and electricity consumption, Razzaghmanesh, Beecham, & Salemi (Razzaghmanesh, Beecham and Salemi, 2016) found that adding vegetation on 30% of the total rooftop area in a high-rise densely populated area and, thus lowering building surface temperatures by 0.06 °C, could lead to corresponding electricity savings of almost 2.6 $W/m^2/day$ in the considered region. In favor of greening urban spaces, compared to the alternative of high albedo materials to lower urban ambient temperatures at the pedestrian level, M. Taleghani (Taleghani, 2018) arises as an important factor the re-radiation of sun to the pedestrians through these highly reflective materials.

It is also interesting to compare the performance of green roofs in tropical and temperate oceanic climates. In tropical areas, like Sri-Lanka and Singapore, reduction of heat gains during an entire summer design day can exceed 13.0 KWh/m^2 (Yang *et al.*, 2018), while simulated temperatures at 1.5 m above ground for the total rooftop's surface greening scenario are 1.76 °C lower than the ones in the initial conventional case (Herath, Halwatura and Jayasinghe, 2018). In temperate oceanic areas, research results are more contradictive. For example, simulation results showed a cooling capacity of green roofs of the order of 0.5 °C in the dense examined area of Vienna (Austria) (Žuvela-Aloise *et al.*, 2018). However, sedum-planted green roofs with shallow substrates in Utrecht (The Netherlands) offered slight cooling effects in an altitude close to the ground and those only during nighttime (Solcerova *et al.*, 2017).

One of the main contributions of green roofs is controlling the increased stormwater runoff inside built areas, with the level of their efficiency being strongly dependent on the various climatic conditions prevailing on site (Akther *et al.*, 2018).

Indicatively, in common wet and cold Nordic climates, accrued retention varied from 11% to 30% on an annual basis and from 22% to 46% in May through October (Johannessen, Muthanna and Braskerud, 2018). Similarly, the simulated runoff curtailment performance of a green roof in different Canadian climates varied from 17% to 50% for drought-resistant plants (Talebi *et al.*, 2019). In addition, two green roofs with different substrate depths, 125mm and 75 mm, could retain approximately 33% and 23% of entire precipitation, respectively, with the experimental installations placed in Portland, Oregon, an area with temperate climate similar to that of the Mediterranean (Schultz, Sailor and Starry, 2018).

Green roofs are an important tool for the management of storm water run-off in cities, where wide-scale implementation can ultimately reduce urban flood events (Volder and Dvorak, 2014; Hashemi, Mahmud and Ashraf, 2015; Karteris *et al.*, 2016). Percentage-wise, the retention levels can range from 35.5% to 100%, with a mean retention of 77.2% according to Zhang et al. (Zhang *et al.*, 2015). Moreover, a total average retention of 66% of a full-scale extensive green roof has been found by Nawaz et al. (Nawaz, McDonald and Postoyko, 2015). In absolute terms and for optimal conditions, storm water storage capacities can vary from 25 mm to 40-50 mm (Johannessen, Hanslin and Muthanna, 2017).

In an effort to investigate the parameters affecting the retention efficiency of green roofs, a stochastic weather generator coupled with a conceptual hydrological model has recently been used (Viola, Hellies and Deidda, 2017). The results of this study point out that the water retentiveness is proportional to the soil depth, with humid subtropical climates being in favor of a green roof's retention performance and in contrast with Mediterranean ones. Following also a simulation approach, Szota et al.

(Szota, Farrell, *et al.*, 2017) used a water balance model to propose that the rainfall detention capacity can increase with the appropriate combination of irrigation regimes and drought tackling strategies. Other parameters that play a determining role in the hydrological performance of green roofs are the vegetation characteristics and the physical properties of the layers' components (Cipolla, Maglionico and Stojkov, 2016; Szota, Fletcher, *et al.*, 2017).

The remaining water that escapes green roofs during intensive precipitation events can lead to leakage of nutrients and metals and thus negatively affect the quality of downstream water bodies, especially in the case of recently applied constructions (Buffam, Mitchell and Durtsche, 2016). This implication can be mainly attributed to high organic matter of the soil substrate leading to more brownish color, dissolved salts and higher nutrient concentrations like phosphorous in the removed water (Beecham and Razzaghmanesh, 2015; Hill, Drake and Sleep, 2016a). According to Wang et al. (Wang, Tian and Zhao, 2017), adding an absorption layer comprising a mixture of active charcoal and/or pumice with perlite and vermiculite below the growing medium is sufficient to achieve the desirable balance between water runoff attenuation, pollution amelioration and optimal service lifetime of a green roof.

Apart from climatic conditions, water run-off management efficiency of green roofs is also affected by precipitation depth (Todorov, Driscoll and Todorova, 2018) and the aging of the substrate layer (Bouzouidja *et al.*, 2018) whose relationship with retention is directly inverse. In the same direction, an experimental study by K. Soulis et al. (Soulis, Ntoulas, *et al.*, 2017) and a simulation study by K. Soulis et al. (Soulis, Valiantzas, *et al.*, 2017) show that larger reductions in water run-off quantities are present for higher substrates, lower initial substrate moisture content, and smaller rainfall amount.

Although research on the environmental impact of vegetated water sensitive urban design (WSUD) measures -among which lie green roofs- has strongly grown during the last years, less attention has been attributed to the carbon sequestration potential (Kavehei *et al.*, 2018). Similarly, L. Whittinghill et al. (Whittinghill *et al.*, 2014) mention that carbon dynamics in terms of sequestration and storage have been little examined in green roofs in contrast to natural and agricultural landscapes.

Nevertheless, some researchers have tried to shed light on this type of ecosystem service provided by green roofs. The aboveground and underground carbon content of various green roof landscape systems for two growing seasons after the first plant establishment was estimated by L. Whittinghill et al. (Whittinghill *et al.*, 2014), and an amount of 67.70 kg C/m^2 for the roofs planted with herbaceous perennials and grasses was found. Getter & Rowe (Getter and Rowe, 2009) examined different types of extensive and semi-intensive green roofs with Sedum as their primary plant and concluded that the above- and below-ground vegetation carbon storage can be in the range of 64 – 239 g/m^2 and 37 – 185 g/m^2, respectively. In contrast, Agra et al. (Agra *et al.*, 2017) experimentally examined the photosynthetic activity at the leaf level of Sedum planted green roofs and found increased rates of CO_2 emissions during daytime, which could not be completely offset by the net carbon assimilation during night hours. This tendency might be due to the incorrect substrate watering patterns followed for the specific plant species (Kuronuma and Watanabe, 2017).

Following a Life Cycle Assessment (LCA) approach, Kavehei et al. (Kavehei *et al.*, 2018) showed that the initial embodied carbon related to production, transportation and construction stages plays the most significant role in the overall carbon footprint of green roofs and that their carbon storage capacity can compensate for approximately 68% of the carbon footprint throughout their lifetime. Moreover, the payback time for green roofs' CO_2 sequestration potential to offset the CO_2 emitted throughout the production phase and the maintenance procedures, approximately varies between 6 and 16 years, a time period well within the lifespan of extensive green roof systems (Kuronuma *et al.*, 2018).

Recent studies have attempted to jointly examine green roof infrastructure application and urban design conditions by exploring the interactions between morphology of urban canyons and urban heat magnitude under various climatic conditions (Aflaki *et al.*, 2017a). In their recent review, E. Jamei et al. (Jamei *et al.*, 2016) distinguished four characteristics of urban design that directly affect outdoor thermal comfort, i.e. aspect ratio, sky view factor, street orientation, and local and neighborhood scale. After simulating different urban models of discrete level of compactness in the Netherlands, M . Taleghani et al. (Taleghani *et al.*, 2015) concluded that direct solar radiation and mean radiant temperature, which are affected by urban design, have the lion's share in thermal comfort adjustment. They also demonstrated that the most comfortable building arrangement form in terms of microclimatic conditions is the courtyard. For the case of a warm humid city of India, simulation results suggested that if the studied area's canyon aspect ratio is equal to 2.5 and its orientation angle with the direction of wind ranges from 30° to 60°, the Physiologically Equivalent Temperature (PET) around mid-afternoon of summer design day can decrease by up to 9 °C (De and Mukherjee, 2018).

When it comes to green infrastructure, green roofs combined with plants on the ground provide stronger cooling effects in the case of taller buildings, while higher urban density values (percentage of built-up area) lead to increased temperatures in a typical Mediterranean climatic zone (Perini and Magliocco, 2014). Another study by Kim, Gu, & Kim (Kim, Gu and Kim, 2018) showed that green roofs hardly contribute to urban thermal stress mitigation, when a high-rise urban canopy model is examined, while increase of the grass- and tree-covered areas, particularly in hot climatic conditions, is a more efficient measure. Finally, after comparing three distinct district layouts, namely scattered, enclosing and array, and scrutinizing different green roof formations in Chongqing (29°N, 106°E), China, C. Jin et al. (Jin *et al.*, 2018) suggest that scattered layout and central placement of green roofs upwind can cause sufficient air cooling of the entire investigated area.

For a big number of large cities around the world, Estrada, Botzen, & Tol (2017) claim that global and local climate change jointly create negative economic effects and if local initiatives on attenuating UHI are neglected, mitigation efforts on global climate change can lose great part of their effectiveness towards curtailing severe climate impacts. According to their recent study, with UHI effects taken under consideration, the percentages of lost Gross Domestic Product (GDP) for the median city of those examined are 1.4% and 1.7% in 2050 for the RCP 4.5 and RCP 8.5[1], compared to 0.7% and 0.9% loss, respectively, due to global climate change alone. In

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[1] According to the Representative Concentration Pathway (RCP) adopted by the IPCC for its 5th Assessment Report (AR5) in 2014, global annual GHG emissions (measured in CO_2-equivalents) reach maximum in 2040 and decrease afterwards in RCP 4.5, while in RCP 8.5, emissions keep increasing throughout the 21st century (Prather *et al.*, 2013)

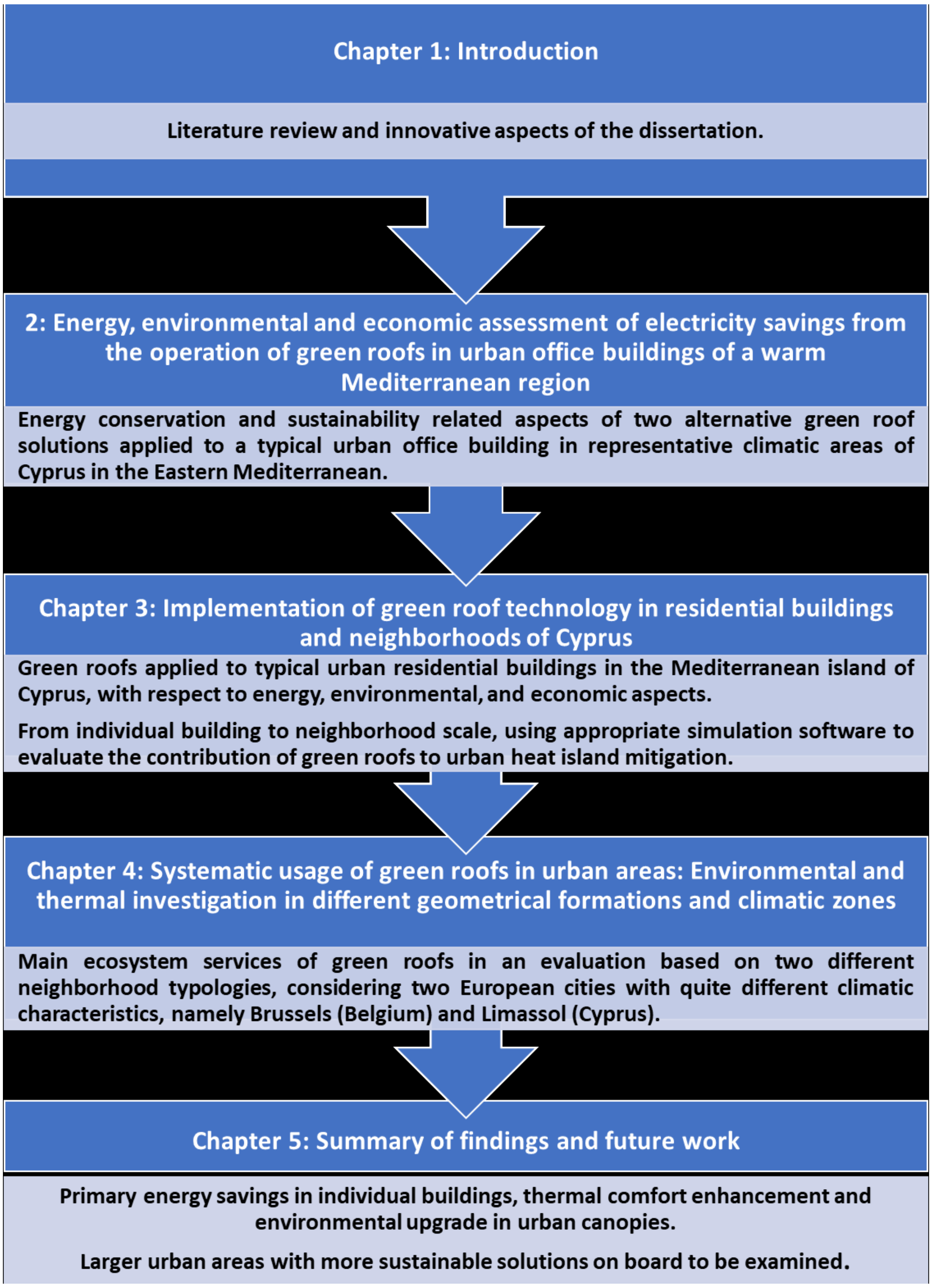
this direction, Peng & Jim (2015) suggest that a wider application of policies promoting green roof installations in modern and densely populated cities, like Hong Kong, can help towards combating climate change, with the entire yearly monetary value of district-scale implementation of extensive green roofs being USD 12.98 million with unit value of USD 10.77 m^{-2} $year^{-1}$. Even when local environment is of primary interest, this nature-based solution can still be effective, although the accompanying high installation and maintenance costs may be deterring factors for building owners to invest (Sproul *et al.*, 2014).

Several studies have attempted to quantify the economic performance of green roofs in urban areas. Starting from the most recent ones, the discounted payback period of such investments in a Mediterranean city ranges between 13 and 18 years, when savings in energy costs, the economic gains regarding NO_2 uptake and the avoided municipal storm water fees are considered (Cascone et al., 2018). Going one step further, Berto, Stival, & Rosato (2018) make a more detailed analysis considering both private and social benefits (e.g. aesthetics, air quality enhancement, environmental protection), with the latter handled as externalities that are monetized in order to be adherently processed for the promotion of green roofs in the same area. Sensitivity analysis showed that a 74.0% probability of a positive net present value exists, when positive externalities are included in the analysis.

A similar rationale is followed by other studies, where cost-benefit analyses of several green roof installations are performed, which show that aesthetic aspects, sound insulation, air pollution mitigation, and confinement of municipal stormwater infrastructure (among others) mostly affect the overall economic value. Some adverse effects of green roofs should also be taken into consideration, which can be a higher initial installation cost than traditional roofs, an increase in weight load that may require enhanced structural support, and extra maintenance costs (Bianchini and Hewage, 2012b; Claus and Rousseau, 2012; Teotónio, Silva and Cruz, 2018).

1.2 Structure of the dissertation

This doctoral dissertation consists of 3 main chapters. These chapters explore the energy, environment and economic benefits associated with the deployment of green roofs. Effort is given in developing the research methodology from an individual building to a whole neighborhood scale, in order to estimate the contribution of green roofs as a measure of green infrastructure. The following diagram shows the connection of the chapters of this dissertation and includes main points of interest.



Chapter 1: Introduction

Literature review and innovative aspects of the dissertation.

2: Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region

Energy conservation and sustainability related aspects of two alternative green roof solutions applied to a typical urban office building in representative climatic areas of Cyprus in the Eastern Mediterranean.

Chapter 3: Implementation of green roof technology in residential buildings and neighborhoods of Cyprus

Green roofs applied to typical urban residential buildings in the Mediterranean island of Cyprus, with respect to energy, environmental, and economic aspects.

From individual building to neighborhood scale, using appropriate simulation software to evaluate the contribution of green roofs to urban heat island mitigation.

Chapter 4: Systematic usage of green roofs in urban areas: Environmental and thermal investigation in different geometrical formations and climatic zones

Main ecosystem services of green roofs in an evaluation based on two different neighborhood typologies, considering two European cities with quite different climatic characteristics, namely Brussels (Belgium) and Limassol (Cyprus).

Chapter 5: Summary of findings and future work

Primary energy savings in individual buildings, thermal comfort enhancement and environmental upgrade in urban canopies.

Larger urban areas with more sustainable solutions on board to be examined.

Figure 1: Doctoral dissertation's flow chart

As shown in the above diagram, **Chapter 2** explores the potential benefits of green roofs not only on energy conservation but also on other sustainability aspects. The analysis focuses on a typical reference office building in Cyprus under various building thermal insulation (BTI) scenarios. Native plants of Cyprus and the corresponding conservative irrigation regimes are carefully selected and ways to exploit recycled urban resources (rubber crumbs and waste compost) are considered. The economic viability of the proposed green roof alternatives is examined using a comprehensive approach that accounts not only for the possible monetary benefits from energy savings, but also for the economic benefits of a reduced environmental impact, in terms of avoided costs of emissions of Carbon Dioxide (CO_2), Sulphur Dioxide (SO_2), and Nitrogen Oxides (NO_x).

Adding to this research, which focused on buildings of the tertiary sector, **Chapter 3** provides a holistic evaluation of the positive contribution of green roof technology to urban residential conditions of the Mediterranean island of Cyprus. The energy, environmental and economic aspects related to the application of green roofs to a typical two-story single-family building and a typical four-story multi-family one in four major cities (Nicosia, Larnaca, Limassol, and Paphos) are examined. Moreover, the scope of the research is expanded from the individual building perspective to a characteristic neighborhood scale implementation in order to assess the impact of green roofs on the Urban Heat Island (UHI) mitigation.

Chapter 4 presents an assessment of the environmental upgrade of built-up areas facilitated by the employment of green infrastructure in accordance with the urban morphology characteristics of each area. In order to achieve this, a first attempt is made to comprehensively incorporate the ecosystem services in an evaluation based on the examined morphological parameters of the neighborhood typologies, considering two European cities with quite different climatic characteristics, namely Brussels (Belgium) and Limassol (Cyprus). The proposed evaluation is based on simulation results regarding both the urban thermal comfort enhancement and the CO_2 sequestration potential, as well as recent well-documented literature values that concern water retention capacity.

1.3 Innovative aspects of the dissertation

This research provides a comprehensive assessment of green roof technologies for commercial and residential buildings in Cyprus. As evident from the literature review previously presented, as well as from the literature review of each subsequent chapter, this work is one of the few studies to explore the energy savings of such nature-based solutions under Mediterranean climatic conditions. Moreover, sensitivity analysis for the economic viability of green roofs as well as examination of microclimatic effects of their systematic urban usage have been jointly included. The following scientific articles stemming from this research work have already been published in peer-reviewed journals:

a) I. Ziogou, A. Michopoulos, V. Voulgari, T. Zachariadis, Implementation of green roof technology in residential buildings and neighborhoods of Cyprus, Sustainable Cities and Society. 40 (2018) 233–243.

b) I. Ziogou, A. Michopoulos, V. Voulgari, T. Zachariadis, Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region, Journal of Cleaner Production. 168 (2017) 346–356.

This dissertation expands the scope of the analysis for green roofs by including the assessment of the monetary benefits due to avoided damage costs because of lower emissions of carbon dioxide and local air pollutants. This is an important aspect because, according to the results, the alternative green roof options that have been examined, offer substantial energy and environmental benefits compared to buildings with conventional roofs, which in turn offers economic benefits due to avoided energy import costs and avoided pollution-related damages. Although green roof investments in the residential sector, in most cases, are still not cost-effective because of high installation costs, the sensitivity analysis provided in the thesis has demonstrated that green roofs become economically viable with only modest reductions in their installation cost, which are possible in the medium term because of technological progress or learning-by-doing due to their increased deployment. This prospect can be encouraging for local homeowners or real estate developers to eventually include green roofs in their preferable building's envelope upgrades.

In addition, the extensive energy, environmental and economic analysis of these passive building design solutions is combined in a novel way with an examination of their contribution to the upgrade of urban micro-climatic conditions. In this context, the results of this thesis can be considered representative for most Mediterranean areas since climatic characteristics, building regulations, and urban planning conditions in the region are broadly similar with the ones prevailing in Cyprus.

Finally, this dissertation contributes directly to one of European Union's fundamental policy challenges, namely addressing climate change in a scientifically appropriate way and consequently promoting nature-based solutions directed towards urban-scale application. The results can help the formulation of policy tools for assessing both the effectiveness and the applicability of such urban resilience measures, since they provide – in addition to the observations and results in the existing literature – helpful insights regarding basic ecosystem services of green roofs with respect to geometric and climatological characteristics of different urban formations.

2 Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region

Green roofs are an important technique to efficiently mitigate adverse environmental impacts of buildings. This chapter[2] focuses both on energy conservation and sustainability related aspects of two alternative green roof solutions applied to a typical urban office building in representative climatic areas of Cyprus in the Eastern Mediterranean. Simulations regarding the buildings' energy demand were conducted using EnergyPlus software (DOE. Department of Energy; US, 2017). Based on these results and using an in-house algorithm, the primary energy consumption for each alternative solution was computed, assuming variable refrigerant flow air-to-brine heat pump as heating and cooling system, coupled with a calculation of the associated emissions of carbon dioxide, nitrogen oxides and sulphur dioxide.

The analysis shows a reduction in primary energy consumption up to 25% in heating and up to 20% in cooling operation, thanks to the use of green roofs, and a corresponding reduction in emissions. The economic viability of the proposed green roof solutions was also examined, taking into consideration both monetary and environmental costs. The results show that the green roof solutions increase the lifetime cost up to 40,000 €, however they can lead to additional environmental and economic benefits which are hard to quantify.

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[2] Work presented in this chapter appeared in the following publication: I. Ziogou, A. Michopoulos, V. Voulgari, T. Zachariadis, Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region, *Journal of Cleaner Production* 168 (2017) 346–356.

2.1 Introduction

It is widely evident that the most prosperous societies worldwide are those whose service sector exhibits a strong and growing contribution to national economic output. Such a strong growth, however, inevitably increases the sector's ecological footprint. In the European Union, for example, final energy consumption has followed a declining path in the last years. This trend is mainly due to the reduction of final energy consumption in the sectors of industrial production, transportation, and households. On the contrary, the service sector has followed a different path: its energy consumption has risen by approximately 5.7% during the same period (EEA, 2015).

Among others, the application of green roof technology on the rooftops of commercial buildings is one of the promoted solutions to mitigate the relevant energy, environmental and climate impacts (Ascione, 2017; Viola, 2017). In principle, a green roof is the roof of a building that it is partially or completely covered with vegetation and a growing medium (such as soil or gravel). It can be applied either as a retrofit of the existing building's envelope or at the construction phase of new buildings, affecting not only the building's energy and environmental performance but also the microclimate of the surroundings (Skelhorn, Levermore and Lindley, 2016b; Aflaki *et al.*, 2017b; Vacek, Struhala and Matějka, 2017).

In this chapter we analyze the energy aspects of green roof technology in Cyprus, a semi-arid island located in the Eastern Mediterranean. Following the EU-wide trend, the commercial and public service sector is responsible for a substantial portion of total energy consumption of Cyprus, with a share of more than 14%, which is slightly lower than that of the residential and clearly higher than that of the industry sector (IEA, 2014). Since most of the commercial buildings are placed in the four major cities of Cyprus (Paphos, Limassol, Larnaca, and Nicosia), it is essential to focus any analysis on the increasing energy use of this sector in urban areas. In general, cities are responsible for 70% of anthropogenic carbon dioxide (CO_2) emissions and a surge in air pollution, turning them into not only a basic perpetrator but also an immediate victim of climate change (Rigter, Saygin and Kieffer, 2016).

A considerable research effort has been devoted to analyzing the energy, environmental and economic aspects of green roofs. In China, for example, Yang et al. (2015) analyzed air conditioning electricity consumption and temperature recordings of various roof structures (including vegetated, clay and ceramic coatings) of a commercial building in Guangzhou. Two different studies were conducted in Hong Kong. The first one (Chan and Chow, 2013a) investigated both the energy performance and the cost payback period of a green roof system under distinct forthcoming climatic conditions, while the second one (Chan and Chow, 2013b) updated the Overall Thermal Transfer Value (OTTV), which is a method of calculating possible building envelope's heat gains, with a set of correction factors, in order to be applicable in the cases of planted rooftops.

In the US, alternative methods were employed to evaluate the energy performance of green roofs. Moody and Sailor (2013), developed the ratio of Heating, Ventilation and Air-Conditioning (HVAC) energy consumption for a building with a traditional roof to that of a building of with a planted roof, called Dynamic Benefit of Green Roofs (DBGR), while Yaghoobian and Srebric (2015) simulated different case studies using the Department of Energy (DOE) commercial reference building models Moreover, in the UK, green and cool roof renovating technologies were examined in contrast to the application of traditional insulation in a classic office building located in Central London (Virk *et al.*, 2015).

Regarding the Mediterranean region, where similar climatic conditions prevail, recent studies have attempted to evaluate the impact of this technological solution through various approaches. Indicatively, based on experimental and numerical analysis, green roofs can lead to the reduction of energy both entering the building during heating days and exiting the building during cooling days, with the lack of increased insulation being in favor of the overall energy performance (Bevilacqua *et al.*, 2016; Silva, Gomes and Silva, 2016). In addition, Costanzo et al. (2016) and Karachaliou et al. (2016) showed that the Urban Heat Island (UHI) effect can be mitigated efficiently with the implementation of green roof technology. Finally, regarding shallow green roofs, Bevilacqua et al. (2015) found that the spatial factor constitutes an important determinant in terms of overall thermal performance and vegetative arrangement.

Adding to the analyses of previous studies that were mentioned above, in this chapter we explore the potential benefits of green roofs not only on energy conservation but also on other sustainability aspects. The analysis focuses on a typical reference office building in Cyprus under various building thermal insulation (BTI) scenarios. We carefully select native plants and the corresponding conservative irrigation regimes, and consider ways to exploit recycled urban resources (rubber crumbs and waste compost). We examine the economic viability of the proposed green roof alternatives using a comprehensive approach that accounts not only for the possible monetary benefits from energy savings, but also for the economic benefits of a reduced environmental impact, in terms of avoided costs of emissions of Carbon Dioxide (CO_2), Sulphur Dioxide (SO_2), and Nitrogen Oxides (NO_x). Although based on an individual case study, our findings can be expanded in order to estimate the effects of such a technology on a wider urban scale, which can lead to useful policy recommendations for the broader adoption of green roof systems.

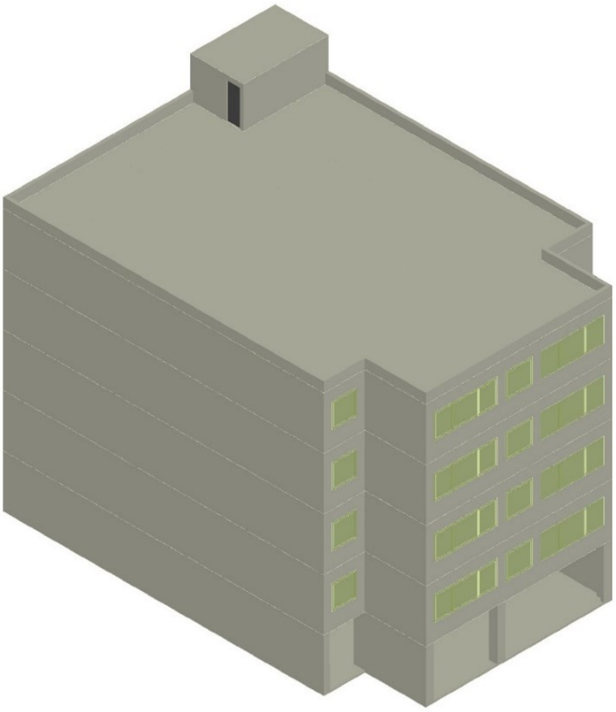
2.2 Methodology

2.2.1 Building features

The determination of the geographical and morphological characteristics of the typical office building in Cyprus was based on a detailed analysis of the current typology of this country's building stock. The relevant information has been mainly obtained from the Statistical Service of Cyprus (CYSTAT, 2015) and has been enhanced through contacts with planning and construction engineers as well as site visits.

The service sector's buildings constitute approximately 34% of the existing building stock, with stores and offices accounting for more than half of them (CYSTAT, 2015). They are primarily located in the city areas, and their height varies depending on the type of urban zone they fall into. On average, they are developed in 4 stories above ground floor, which is usually formed as an open pillared space. The covered surface rarely exceeds 1,500 m^2, and their typological characteristics include expanded areas of transparent structural elements and the absence of balconies.

Based on the aforementioned description, a new typical office building has been designed from scratch, in accordance with common design and construction practices in Cyprus, in order to be considered representative of this specific category's building stock. It is a four-story building that incorporates a pilotis[3] in the ground floor and has a rectangular 365 m^2 floor plan, identically repeated in all stories. The building has two independent free sides, the south and west ones, while the north and east ones are in direct contact with adjacent properties and accommodate both the supporting and communal areas. The office rooms are spread across the free sides of the building, while the common areas, storage and server room, and the conference room are located in the blind ones and in the core of it. The three-dimensional representation of the office building is presented in Fig. 2.



(a)

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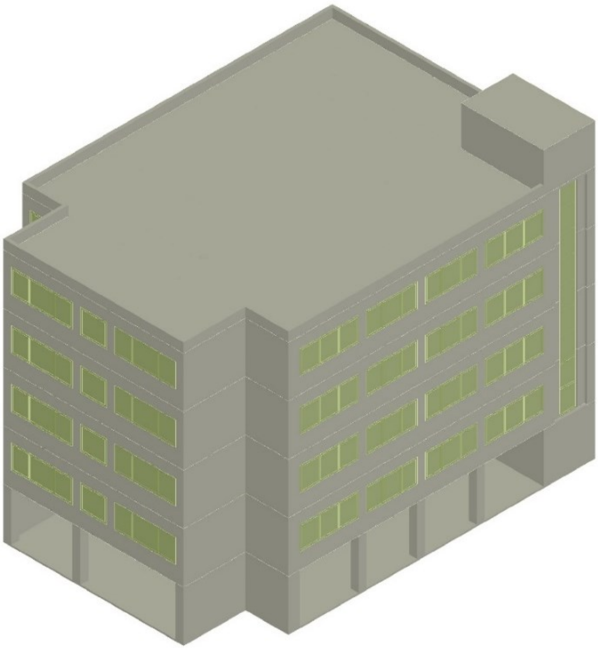
[3] Pilotis are columns or similar structural elements that support a building above ground.



(b)

Figure 2: Isometric front view of the simulated office building; North-West view *(a)* and South-West view *(b)*

The load bearing structure and the masonry are made of reinforced concrete and perforated bricks, respectively. In some of the examined cases, extruded polystyrene is used as a thermal insulation layer. It is applied on the outer side of the vertical structural elements and the ceiling above the pilotis. The heat insulation thickness values derive from the relevant requirements for the maximum thermal transmittance (U-value) of the current regulation (MECIT, 2015a) and are presented in Table 1.

Table 1: Thermal transmittance values (U values) of the buildings' opaque elements

Building component	Insulation thickness [mm]	U value [W/(m^2·K)]	
		Uninsulated	Insulated
External elements made of reinforced concrete	40.0	3.56	0.62
External masonry	30.0	1.39	0.59
Vertical elements made of reinforced concrete in contact with unheated space	40.0	2.65	0.59
Masonry in contact with unheated space	30.0	1.25	0.65
Floor over pilotis	40.0	2.80	0.59
Ground floor	40.0	3.28	0.61
Rooftop*	40.0	3.28	-

*Rooftop remains uninsulated in all cases

As shown in Figure 2, windows are allocated along the south -main- and west sides of the building and occupy 35% to 40% of their surface, whereas the north and east sides are made exclusively out of opaque elements, in accordance with common design and construction practices in Cyprus. Windows bear an aluminum frame with thermal break and a thermal transmittance (U_f-value) equal to 2.98 W/(m^2·K) and double glaze with thermal transmittance (U_g-value) equal to 2.8 W/(m^2·K). It is worth noticing that for the above given values the external openings can meet the legislative provisions of the minimum energy efficiency requirements with regard to Decree 359/2015 (MECIT, 2015a).

2.2.2 Climatic and geographical features

Cyprus' geographical position is Latitude 35° North, Longitude 33° East, and its climate is determined by strong Mediterranean characteristics (MOA, 2016a). Based on the Köppen-Geiger Climate Classification (KGCC) and the respective high resolution Google Earth maps (Kottek *et al.*, 2006; Rubel *et al.*, 2017), Cyprus is divided into two main climatic zones. The first one which is categorized as Csa, i.e. warm temperate with hot and dry summers, comprises the central, southern, western and partly northern regions of the island, while the eastern region along with Karpass Peninsula and the remaining northern areas are included in the other climatic zone described as BSh, i.e. hot semi-arid.

Nicosia, which is the capital of Cyprus, along with Limassol and Paphos are located in the central, southern and southwestern parts of the island respectively and are characterized by the Csa climatic features. Larnaca is situated in the southeastern part of the island and belongs to the second climatic zone. Table 2 provides the annual precipitation and temperature fluctuation of the afore-mentioned cities (MOA, 2016).

Table 2: Annual meteorological characteristics (adapted from MOA, 2016)

Climatic indicators	Larnaca	Limassol	Nicosia	Paphos
Average daily temperature (°C)	19.6	20.4	19.7	18.7
Average daily maximum temperature (°C)	24.7	25.4	26.2	23.6
Average daily minimum temperature (°C)	14.5	15.4	13.2	13.9
Average monthly precipitation (mm)	351.5	407.5	342.2	386.7

2.2.3 Green roof components and layers

There are two main types of green roofs: intensive and extensive. They are categorized based on their construction demands and the stratification of layers. The first type is characterized by its deep growing medium layer (0.2-2.0 m), ability to support many kinds of plants, high maintenance and installation costs, and comparatively higher extra dead loads. The second type is distinguished by its shallow substrate (up to 0.15 m), limited availability of appropriate supporting vegetation, minimal installation and maintenance costs, and insignificant added static loads (Vijayaraghavan, 2016).

The energy performance of a green roof is principally determined by the following contributing mechanisms: a) evaporation through the growing medium and evapotranspiration through the vegetation, b) absorption of solar radiation for the photosynthesis requirements of plants, c) shading effects created by the foliage, and d) roof's thermal inertia boost due to the substrate's high heat capacity (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014).

Going from top to bottom, the first two layers of a green roof, i.e. the foliage and growing medium, play the most important role in the energy balance. Convective (sensible) and evaporative (latent) heat flow from the plant and substrate layers primarily adjust the incident solar radiation. This synergy is reinforced by the conductive heat flux into the growing medium and long wave radiative flux to and from the substrate and vegetation layers (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014).

In this research, the extensive form has been selected as a promising energy and environmental retrofit technology. We investigate two separate real case configuration scenarios based on commercially available components. The plants have been cautiously chosen in order to come from native taxa adapted to semiarid Mediterranean climatic characteristics and concurrently correspond to the necessary energy performance limitations. Native vegetation's characteristics are important for the successful establishment and operation of a green roof. These characteristics can be the enhanced endurance against local severe conditions (e.g. intense drought), similar aesthetic results, promotion of biodiversity, and restriction of appearance of other invasive species (Butler, Butler and Orians, 2012).

More specifically, the chosen vegetation coverings are the following: a) Sedum sediforme, a succulent plant with the ability to activate the crassulacean acid metabolism (CAM) mechanism in order to cope with water stress (Nektarios *et al.*, 2014), and b) Helichrysum Orientale L., a Mediterranean aromatic xerophyte with many environmental advantages (Papafotiou *et al.*, 2013). In both cases, a mixture of pumice (P), compost (C) and sand (S) in a proportion of 5P:1C:4S (%v/v) is selected as a growing medium (Sailor, Hutchinson and Bokovoy, 2008). Locally available compost amplifies the sustainable contribution of the green roof, by improving urban biodiversity and limiting the carbon footprint. The organic matter contained in the substrate reduces the density levels, offers higher water retention, and ensures better evaporative cooling effects (Hill, Drake and Sleep, 2016b), while the maximum percentage of 10% decreases the nitrogen and phosphorus amounts that might leak (Vijayaraghavan, 2016).

With respect to the drainage layer, granular materials are suitable for horizontal or slightly sloped roofs like the ones in most of the commercial buildings (Vijayaraghavan, 2016). It is necessary to put new reused materials in place of traditional ones, in an effort to add on the positive environmental effects of green roofs (Bianchini and Hewage, 2012a). Hence, recycled rubber crumbs which present similar water retention capacity with natural puzolana (Pérez *et al.*, 2012) constitute a promising alternative to be used as a drainage layer (Rincón *et al.*, 2014).

Furthermore, an extensive green roof consists of additional layers that contribute to its sufficient and longer-lasting operation. These are the following: a) the filter fabric prevents small fragments of the layer above it (substrate) from entering the layer below it (drainage component); b) the protection element is responsible for added moisture holding and protection; c) the root barrier protects against possible root penetration; d) the water proofing sheet shelters the roof from any unexpected water leakage (Saadatian *et al.*, 2013; Vijayaraghavan, 2016).

According to the previous technical requirements, commercially available materials have been chosen, i.e. Bauder FV 125 as a filter layer, Bauder SV 300 as a protection element, Bauder PE 02 as a separating layer and Bauder PLANT E as a root resistant water proofing membrane (KartECO, 2017). In accordance with ordinary design processes, 80% of the overall roof area is occupied by the vegetation (Zinzi and Agnoli, 2012), while the remaining surface is covered with gravel and acts as an accessible pathway, necessary for the various maintenance requirements (Silva, Flores-Colen and Coelho, 2015).

2.2.4 Model parameters

2.2.4.1 Energy demand of the building's envelope

The Energy Plus software is used for the energy analysis. It is a widely utilized dynamic energy modelling software for simulating building energy efficiency. It is capable of combining various technical benefits, such as coupled heat and mass transfer models, analysis tools regarding heat balance accomplished by radiance and convection mechanisms, and adjustable calculation time steps (DOE, 2017).

The building's typical floor was divided into 16 independent thermal zones, considering the usage and orientation of each space. This resulted in 65 thermal zones in total, including the staircase. In each zone and according to the suggestions of American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE, 2013) and the European Standard EN 15251:2007 (CEN, 2007), the respective desirable values of internal conditions were considered, i.e. the winter-summer internal temperatures, the ventilation rates, the lighting level, the number of occupants, and the efficiency of electrical appliances. Following also the recommendations of American Society of Heating Refrigeration and Air-Conditioning Engineers, the daily, weekly and monthly usage distributions of the previous parameters were created, considering the building's usage on a five-day weekly basis between the hours of 07:00 and 17:00, a time period representative for the operation of service buildings in Cyprus. Table 3 contains the parameters that were used in the simulations in order to calculate the building's energy demand for heating and cooling.

Table 3: Energy demand's simulation parameters of the building's yearly usage distribution

Parameter	Value	Reference/Comment
Operation period	5 days per week from 07:00 to 17:00	with regard to local usage pattern
Heating period	Middle of November to middle of May	with regard to local climate conditions
Required temperature during the operation hours for the heating period	22 °C	(ASHRAE, 2013; CEN, 2007)
Cooling period	Middle of May to middle of November	with regard to local climate conditions
Required temperature during the operation hours for the cooling period	25 °C	(ASHRAE, 2013; CEN, 2007)
Air changes during the operation hours	1.0	(ASHRAE, 2013; CEN, 2007)
Lighting levels	Office: 12 W/m^2 Conference room: 14 W/m^2 Common areas: 6 W/m^2	(ASHRAE, 2013; adapted from CEN, 2007)
Number of occupants	1/10 m^2 of office area	(ASHRAE, 2013)

Except for the building envelope features and the acceptable internal conditions, weather and climate data are also crucial for the energy performance of the buildings. For this purpose, the typical meteorological year (TMY-2) of the examined cities was adopted; this was derived from the meteorological database of METEONORM (version 7.1.11).

2.2.4.2 Ecoroof model description

All the necessary simulation parameters regarding the green roof suggestions are taken into account in the Ecoroof model that has been developed by Sailor (2008) and is incorporated in EnergyPlus. It essentially supports the decision making processes towards the application of a green roof system. The basic characteristics of this model are the following: a) energy balance between substrate and foliage mainly based on FASST vegetation models (Frankenstein and Koenig, 2004), b) simultaneous calculation of foliage's and substrate surface's temperature equations, and c) water balance that is mainly contingent upon irrigation, precipitation and moisture transfer between the upper and lower layers of the soil (DOE, 2016a).

Nevertheless, the moisture-dependent properties such as thermal conductivity of wet soil, which is directly proportional to the water content of the substrate (Sailor and Hagos, 2011; Ouldboukhitine, Belarbi and Djedjig, 2012), volumetric specific heat capacity, and thermal diffusivity are not yet considered in the Ecoroof model. This is due to the instability problems that appear in the conduction transfer scheme of EnergyPlus (DOE, 2016a). The vegetation and growing medium are the only layers of a green roof formation that are used in the calculations. The remaining layers, with drainage materials among them, are simulated separately following the software's common procedures (DOE, 2016a).

Based on data from several studies (Olivieri *et al.*, 2013; Refahi and Talkhabi, 2015; Costanzo, Evola and Marletta, 2016; Silva, Gomes and Silva, 2016), the principal properties that influence the green roof's energy performance are the soil's depth, the vegetation's height, the leaf area index, and the minimum stomatal resistance. These parameters are examined in modified combinations for each of the suggested solution. The irrigation pattern of the green roof is analyzed with respect to the sustainability of water resources and the viability of the recommended plant coverings.

For the succulent plant Sedum Sediforme, the utmost case of no irrigation is examined, since it has been experimentally confirmed that it can endure semiarid conditions for approximately 14 months (Nektarios *et al.*, 2014). For the aromatic xerophyte Helichrysum Orientale L., watering is applied for 25 minutes every third day (Papafotiou *et al.*, 2013). Thus, the influence of moisture's presence (or absence) and the resultant evaporation effects in the substrate can be additionally assessed. Table 4 contains the parameters which are considered in the calculations.

Table 4: Energy simulation parameters for green roof

			Helichrysum Orientale L.		Sedum Sediforme	
Layer	Parameter	Unit	Value	Reference	Value	Reference
Foliage	Height of plants	m	0.15	(Papafotiou *et al.*, 2013)	0.25	(Nektarios *et al.*, 2014)
	Leaf area index	-	3.50	(Varras *et al.*, 2015)	1.75	(Nektarios *et al.*, 2014)
	Minimum stomatal resistance	s/m	125.00	(Kokkinou *et al.*, 2016)	300.00	(Tabares-Velasco and Srebric, 2012)
Substrate	Thickness	m	0.075	(Papafotiou *et al.*, 2013)	0.15	(Nektarios *et al.*, 2014)
	Conductivity of dry soil	W/(m·K)	0.20[*1]	(Sailor, Hutchinson and Bokovoy, 2008)	0.20[*1]	(Sailor, Hutchinson and Bokovoy, 2008)
	Density of dry soil	kg/m^3	1020.00	(Sailor, Hutchinson and Bokovoy, 2008)	1020.00	(Sailor, Hutchinson and Bokovoy, 2008)

	Specific heat of dry soil	J/(kg·K)	1093.00	(Sailor, Hutchinson and Bokovoy, 2008)	1093.00	(Sailor, Hutchinson and Bokovoy, 2008)
	Thermal absorptance	-	0.96	(Sailor, Hutchinson and Bokovoy, 2008)	0.96	(Sailor, Hutchinson and Bokovoy, 2008)
	Solar absorptance	-	0.85*2	(Sailor, Hutchinson and Bokovoy, 2008)	0.83	(Sailor, Hutchinson and Bokovoy, 2008)
	Saturation Volumetric Moisture Content of the Soil Layer	-	0.26	(Sailor, Hutchinson and Bokovoy, 2008)	0.13	(Sailor, Hutchinson and Bokovoy, 2008)
Watering	Irrigation Rate Schedule Name	m/h	$0.9*10^{-5}$	(Papafotiou *et al.*, 2013; Van Mechelen, Dutoit and Hermy, 2015)	*No irrigation*	(Nektarios *et al.*, 2014)

*1 The actual value is equal to 0.17. However, the minimum value accepted is 0.2 (DOE, 2016b).

*2 The actual value is equal to 0.89. However, the maximum value accepted is 0.85 (DOE, 2016b).

2.2.4.3 Simulation of the heating and cooling system

The simulation of the heating and cooling system aims to calculate the final energy consumption per fuel type in order to maintain the desirable indoor conditions all year round. For this purpose, a central heating and cooling system is considered, using a variable refrigerant flow (VRF) air-to-brine heat pump and fan-coil units. The selection of this system is based on the fact that the VRF systems are widely used in commercial buildings in Cyprus during the construction of new plots and the renovation of existing ones.

The electricity consumption of the reference office building was calculated on an hourly basis, using an in-house developed spreadsheet based on: (a) the building's energy need, as it is provided by EnergyPlus simulations, (b) the ambient air-temperature retrieved from the Meteonorm weather files, and (c) the Coefficient of Performance (COP) or Energy Efficiency Ratio (EER) of the heat pump resulting from the manufacturer's technical data sheets with reference to the ambient air temperature and heat pump's load (Daikin, 2013).

2.3 Results and discussion

The alternative scenarios that have been examined are briefly the following: 1a. Uninsulated building with conventional roof; 1b. Uninsulated building on which the two types of proposed green roofs are placed; 2a. Perimetrically insulated building (including the pilotis roof) with conventional roof; 2b. Perimetrically insulated building (including the pilotis roof) on which the two types of suggested green roofs are placed again.

2.3.1 Energy evaluation

The energy efficiency of the selected green roof solutions was estimated by comparing the annual primary energy consumption per square meter of the building's conditioned area for each one of the six alternative scenarios. We chose to use primary energy consumption instead of final energy consumption, e.g. electricity consumption, in this evaluation based on suggestions of the existing energy analysis literature, e.g. (CEN, 2008; Solmes, 2009; Thiede, 2012) and the fact that this energy form includes the overall efficiency of the energy system, as it takes into consideration the efficiencies of production, distribution and end-use of an energy source. For this reason, the primary energy consumption values can be directly compared with similar values not only in the same energy system, but also between different energy systems, and express system-wide efficiency performance (Solmes, 2009).

The established national primary energy conversion factor (2.7) for the Cypriot electricity production system was used to convert the electricity consumption of the VRF system into primary energy consumption (MECIT, 2015b). The combined values regarding heating and cooling energy consumption and the difference between each examined initial case and the corresponding alternative one, in which the green roof solution is applied, are presented in Fig. 3 and Fig. 4 respectively. The second green roof configuration offers the highest energy savings for heating, reaching 25% lower primary energy needs compared to the no green roof case. Conversely, the first configuration leads to the highest energy savings for cooling, of the order of up to 20%. Overall, the application of green roofs in insulated buildings saves more primary energy (in relative terms) rather than in uninsulated buildings. Despite differences in the climatic conditions, the resulting energy savings are consistent in buildings of all the cities examined.

Moreover and in order to evaluate the influence of the building's orientation on the results, three additional scenarios were examined. The orientation of the reference building was changed from South-North to West-East, North-South, and East-West respectively and the simulation procedures were repeated. The results show that in the West-East orientation, the annual primary energy consumption under the winter operation of the reference building decreased by 6.1%, while in the remaining ones it increased up to 22.2%. In the summer operation, the primary energy consumption decreased up to 13.2% in all cases. These values lead to an overall reduction of the primary energy consumption from 2.7% up to 8.9% in the alternative examined orientations, indicating that the initially selected South-North orientation is the worst-case scenario throughout the year. For this reason, the analysis in the rest of this chapter is limited to the initially selected South-North orientation.

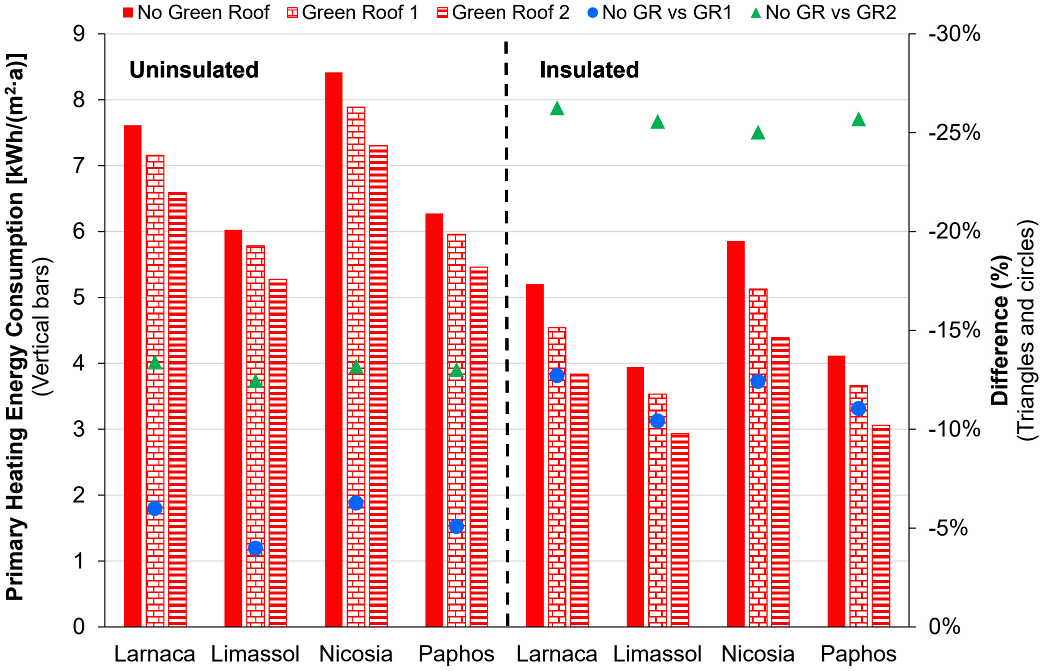


Figure 3: Primary energy consumption under the winter operation of the reference office building.

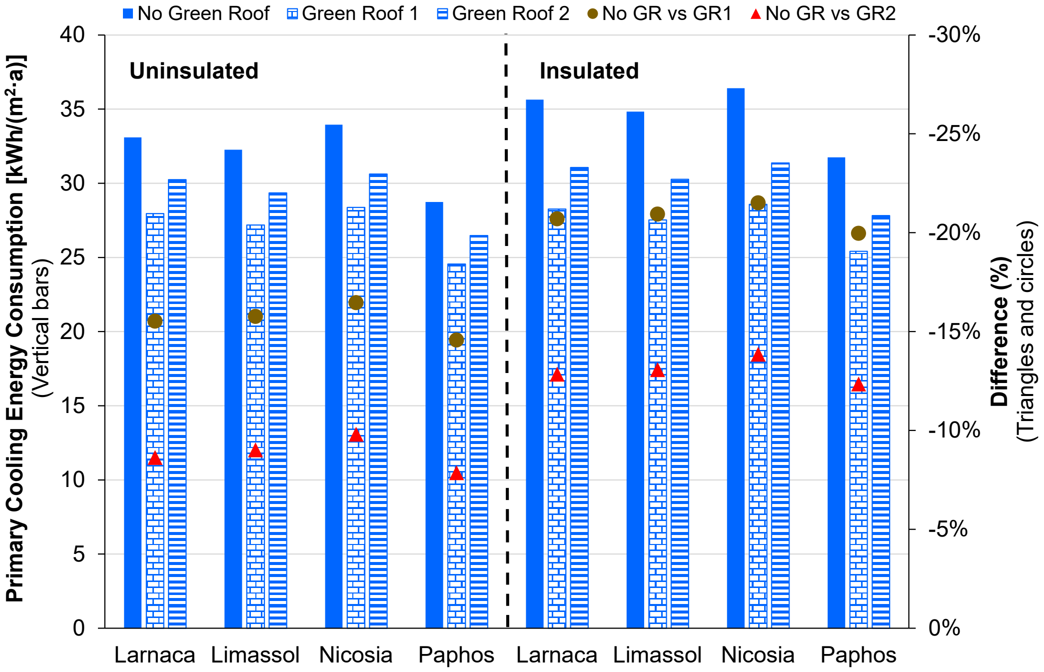


Figure 4: Primary energy consumption under the summer operation of the reference office building.

2.3.2 Environmental assessment

The environmental impact was assessed through a comparative estimation of the emissions of carbon dioxide and two local pollutants of the different proposed green roofs. Assuming, as in Section 2.3.1, that all heating and cooling needs are met through the operation of the electric VRF system, the environmental assessment relies on calculating the indirect emissions released from power generation. Other environmental impacts (e.g. during the entire life cycle of the systems, such as during construction of the buildings and the green roofs) were not considered because they were out of the scope of this study. It should be noted, however, that apart from reduced indirect emissions thanks to lower energy consumption, green roofs offer additional environmental benefits during their operation; an outline of such benefits is provided in the economic analysis of Section 2.3.3 below. Therefore, the environmental assessment that follows has to be considered as conservative, i.e. not revealing the entire range of environmental benefits offered by green roofs in an urban setting.

To compare the indirect CO_2 produced by the VRF system in each of the aforementioned cases, we used the nationally representative conversion emission factor of 0.794 kilograms of CO_2 per kWh of primary energy; this factor reflects the current power generation mix of the energy system of Cyprus (MECIT, 2015b).

The emissions of two dominant air pollutants, NO_x and SO_2, were also taken into consideration. The NO_x emission factor was considered equal to 1.29 tons of NO_x per GWh of electricity produced, based on the current power generation mix of Cyprus (Zachariadis and Hadjikyriakou, 2016). The SO_2 emission factor was calculated based on the weighted average sulphur content (equal to 0.68%) of fuels used for power generation in Cyprus and found equal to 3.94 tons of SO_2 per GWh of electricity produced (Zachariadis and Hadjikyriakou, 2016). Since the analysis provided the electricity consumed during the building's operation, transformation of the respective quantities into power production was firstly conducted, by using the transmission and distribution system's loss coefficient, which was taken equal to 10.6% (EAC, 2015). Subsequently, the calculated produced electricity was multiplied with the respective emission factors of NO_x and SO_2 in order to determine their annual amounts.

The environmental findings are similar to those of Figures 3 and 4 about energy savings: the second green roof alternative leads to the highest emission reductions in heating, whereas the first one is the most environmentally favorable for cooling – irrespective of the city in which the system is applied. Figures 5 and 6 depict the indirect NO_x and SO_2 emissions produced by the VRF system for an entire year, i.e. including both heating and cooling operation. The first green roof alternative leads to higher emission reductions, of the order of 10-15% for uninsulated buildings and about 20% for insulated ones – for both air pollutants and CO_2. In absolute terms, green roofs lead to emission reductions of 3-10 tonnes of CO_2, 2-6 kg of NO_x and 7-18 kg of SO_2 per building per year. The higher values in these ranges come from applications in uninsulated buildings, but percentagewise the positive effect of green roofs is more pronounced in insulated buildings.

Keeping in mind that buildings account for more than 80% of total electricity consumption in Cyprus (Zachariadis and Hadjinicolaou, 2014), and that oil-burning power plants still generate about 90% of total electricity and are the main national emitters of NO_x and SO_2 (Zachariadis and Hadjikyriakou 2016), the contribution of green roofs could be important for mitigating these emissions if employed at a large scale.

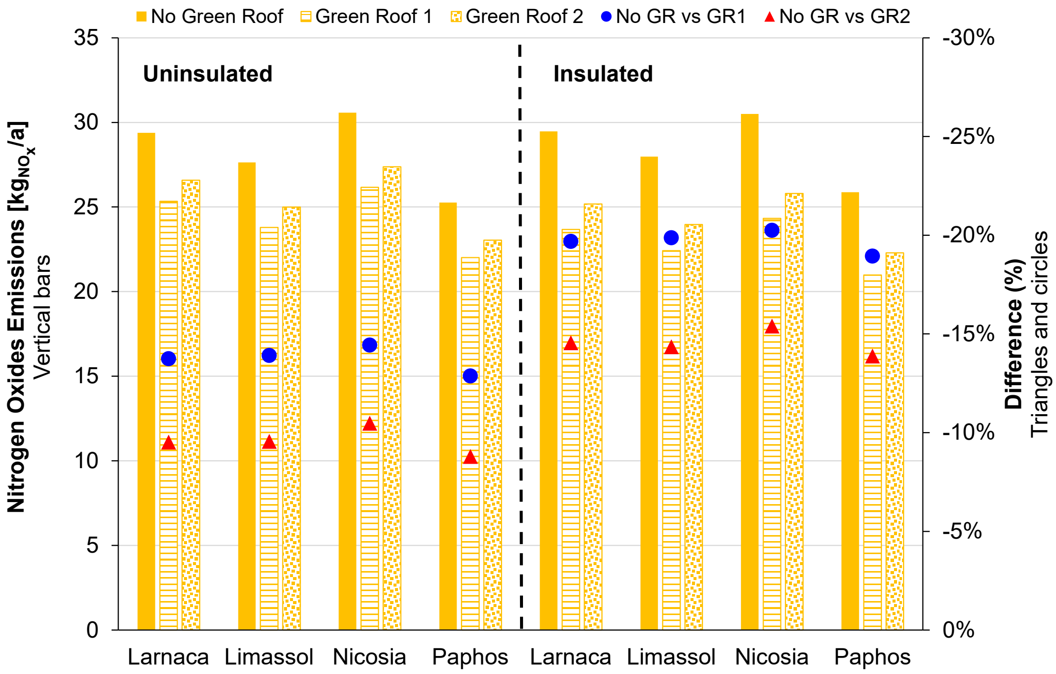


Figure 5: Indirect NOx emissions produced due to electricity consumption of the reference office building per year, for both heating and cooling operation.

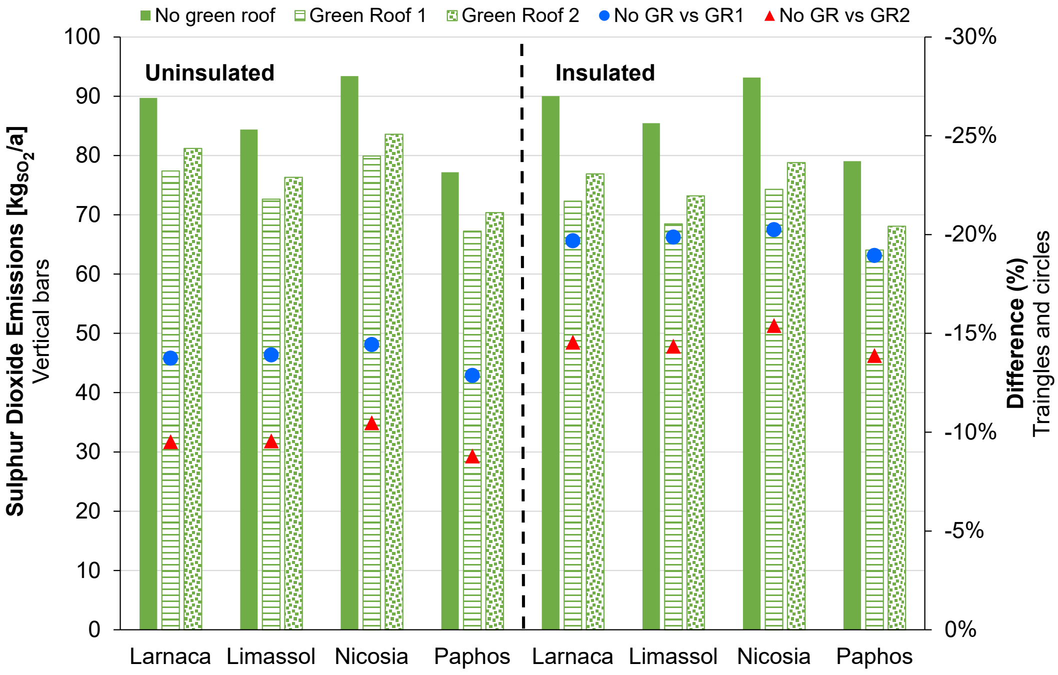


Figure 6: Indirect SO_2 emissions produced due to electricity consumption of the reference office building per year, for both heating and cooling operation.

2.3.3 Economic assessment

The economic evaluation of the green roof technology systems was conducted by calculating the net present value (NPV) of each alternative scenario.

This assessment was based on a social cost-benefit analysis. Thus, apart from electricity costs, the environmental cost due to CO_2, NO_x and SO_2 emissions was also included in the calculations, in order to reflect the expected improvement of social welfare thanks to the avoided economic damages through lower emissions. Thus, the NPV calculation takes into consideration the construction, maintenance, operation, and environmental costs according to the following formula:

$$NPV = -C_o \cdot A - \sum_{i=1}^{n} \frac{MC_i + EC \cdot C_{e,i} + E_{CO_2} \cdot C_{CO_2,i} + E_{SO_2} \cdot C_{SO_2,i} + E_{NO_x} \cdot C_{NO_{x},i}}{(1+r)^i} \qquad (1)$$

In this equation, C_o is the initial installation cost per roof area of the green roof [€/m^2], and A is the roof area [m^2]. MC_i is the green roofs' maintenance cost in i-year [€/a], EC stands for the annual electricity consumption of the air-to-brine heat pump, calculated from the simulation of the VRF system [kWh$_{el}$/a], and $C_{e,i}$ represents the electricity cost in Cyprus in year i [€/kWh$_{el}$]. E_{CO_2}, E_{SO_2}, and E_{NO_x} refer to the annual emitted quantities of CO_2, SO_2 and NO_x [kg/a] respectively calculated in the environmental assessment of Section 3.2, while $C_{CO_2,i}$, $C_{SO_2,i}$, and $C_{NO_x,i}$ is the annual damage cost per mass of CO_2, SO_2, and NO_x emissions respectively [€/kg]. Finally, r stands for the social discount rate [%] and i denotes the year of the examined economic lifetime. The formula has been validated in the following publication: I. Ziogou, A. Michopoulos, V. Voulgari, T. Zachariadis, Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region, Journal of Cleaner Production 168 (2017) 346–356.

For the purpose on this study, the annual maintenance cost of the green roofs is calculated as a percentage of the initial construction cost. Due to the lack of literature data, maintenance costs were assumed on the basis of personal communications with owners of the existing green roof installations in Cyprus. It was found that a value of 3.5% of the initial installation cost is a reasonable approximation of annual maintenance cost for the market conditions of the island. Moreover, the initial installation cost was set equal to 85 €/m^2, which was the existing market price in January 2017 according to personal communication with the company KartECO.

$$MC_i = 0.035 \cdot C_o \cdot A \qquad (2)$$

Electricity costs were based on forecasts of the electricity prices (Zachariadis and Hadjinicolaou, 2014) which had been adopted by the Energy Ministry of Cyprus as a reference case price forecast. As regards the costs per kilogram of CO_2, NO_x and SO_2 used in equation (1), these were obtained from the available international literature, adapted to the economic conditions of Cyprus and assumed to increase over the years, in line with the information provided in detail by Zachariadis and Hadjikyriakou (2016). More specifically, the cost of CO_2 was obtained from estimates of the social cost of carbon (IWG, 2013), ranging from around 35 Euros per ton of CO_2 in 2020 and increasing up to 50 Euros per ton in 2040. The cost of NO_x and SO_2 was adapted from a European external cost assessment study (FEEM, 2008); they range from 7.6 and 13.9 Euros per ton of NO_x and SO_2 respectively in 2020 and increase gradually up to 9.8 and 17.9 Euros per ton of the corresponding pollutant by 2040.

All values regarding the electricity cost and the associated environmental costs are expressed in Euros at constant prices of year 2015. As the evaluation is intended to address a social perspective (and not the behavior of individual investors), a social discount rate of 4% was used, in line with recommendations of public authorities (HM Treasury, 2003; Steinbach and Staniaszek, 2015).

Finally and in order to be in line with the suggestions of the European legislation, an economic lifetime of 20 years was considered (EC, 2012). Figure 7 presents the resulting NPV values.

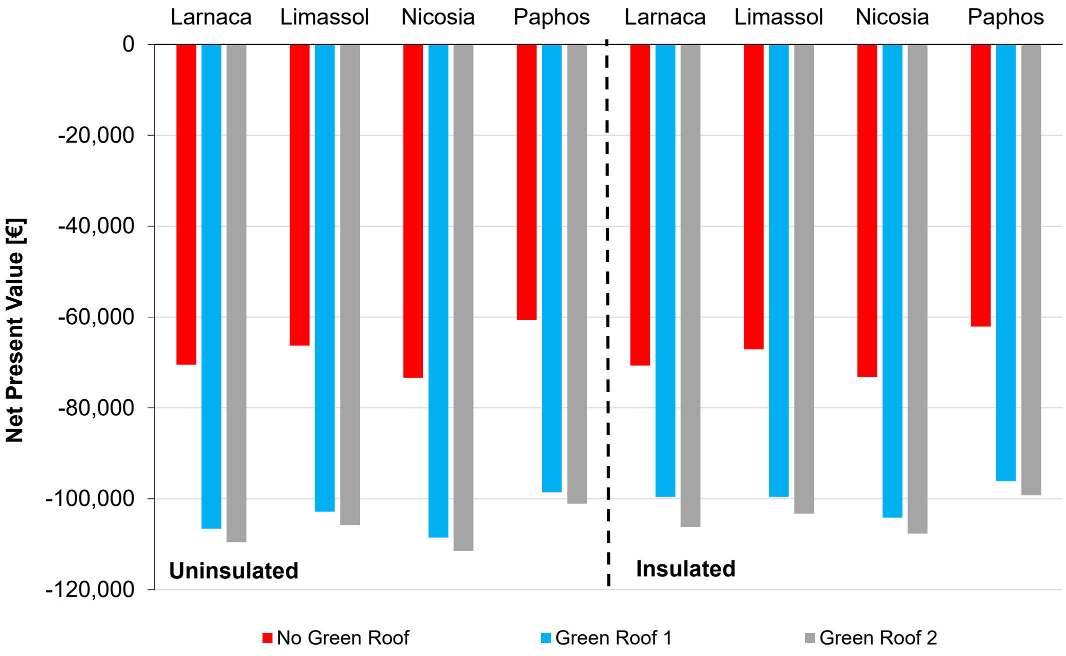


Figure 7: Net present value of the proposed green roof solutions compared with the initial cases.

Although the positive environmental contribution of the examined green roofs is quite significant, as shown in the previous section, their overall NPV value (which is quite similar for the two alternative solutions) remains negative and quite higher than the one of the conventional building types. This is mainly due to the relatively high initial cost of installation and the additional maintenance costs throughout green roofs' lifetime. Both the specialized materials needed and the demanding construction requirements are responsible for the relatively high installation costs.

It is important to keep in mind, however, that the above economic analysis is not complete, as it does not capture additional environmental benefits. Ecosystem maintenance (Bianchini and Hewage, 2012a; Blanusa *et al.*, 2013; Schweitzer and Erell, 2014), aesthetic added value (White and Gatersleben, 2011; Lee *et al.*, 2014), and noise pollution mitigation (Yang, Kang and Choi, 2012; Van Renterghem and Botteldooren, 2014; Connelly and Hodgson, 2015) are additional advantages of green roofs whose economic benefits are difficult to quantify (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014). Even more importantly, flood protection is another environmental service provided by green roofs; water run-off management has recently received increasing attention in Cyprus because of the projections about more intense extreme precipitation events due to climate change (Zachariadis, 2016).

Finally, the above NPV calculations consider a sparse implementation of green roofs at a small scale. However, an extensive implementation of green roofs could improve the micro-climate in urban neighborhoods, which would improve urban resilience to climate change and lead to significant additional environmental and economic benefits. Accounting for all these benefits would provide competent authorities with further information to appreciate the favorable contribution of green roofs.

2.4 Conclusions

This chapter provides a comprehensive assessment of green roof technologies for commercial buildings of Cyprus. Apart from being one of the few studies to explore the energy savings of such nature-based solutions under Mediterranean climatic conditions, the scope of the analysis has been expanded by including the assessment of the monetary benefits due to avoided damage costs because of lower emissions of carbon dioxide and local pollutants.

We considered two alternative green roof options and found that they offer substantial energy and environmental benefits compared to buildings with conventional roofs, reducing the energy needs for both heating and cooling. Primary energy savings for heating in the case of an uninsulated office building range between 6% and 13%, and these values almost double in perimetrically insulated buildings. Similar results, with some differences between the two green roof options, occur for the cooling operation of the buildings. These savings lead to corresponding reductions in CO_2, NO_X and SO_2 emissions. The economic analysis has shown that the green roof technology is still not cost-effective to be implemented in the selected type of office building, despite the monetary energy and environmental benefits. However, additional environmental benefits, which are more difficult to monetize, could be in favor of the financial viability of this solution.

Especially when it comes to city-level environmental upgrades, green roofs may represent either an immediate (Karteris *et al.*, 2016) or a long-term (Mackey, Lee and Smith, 2012) effective solution at a global scale. This prospect should be an additional incentive for the responsible statutory and administrative bodies to adopt policies that promote the design and implementation of urban green roof retrofitting projects.

3 Implementation of green roof technology in residential buildings and neighborhoods of Cyprus

Green roofs are considered as an appropriate nature-based measure to increase the environmental resilience of cities. This chapter[4] examines this technological solution applied to typical urban residential buildings in the Mediterranean island of Cyprus, with respect to energy, environmental, and economic aspects. The analysis shows a clearly positive energy and environmental contribution of green roofs. Although such an investment does not seem to be cost-effective in residential buildings, sensitivity analysis demonstrates that green roofs become financially favorable compared to flat roof constructions with only modest reductions in their current installation cost.

Moreover, green roofs offer environmental benefits that are currently difficult to monetize, which can clearly improve urban resilience to climate change. In order to quantify the impact of green roof installations on the surrounding environment, the analysis was expanded from the individual building perspective to neighborhood scale implementation, using appropriate simulation software to evaluate the contribution of green roofs to urban heat island mitigation**.** Focusing on the ambient air temperature at the pedestrian level, a noticeable decrease was estimated.

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[4] Work presented in this chapter appeared in the following publication: I. Ziogou, A. Michopoulos, V. Voulgari, T. Zachariadis, Implementation of green roof technology in residential buildings and neighborhoods of Cyprus, *Sustainable Cities and Society* 40 (2018) 233–243.

3.1 Introduction

The ongoing global urbanization trend has an indisputable effect on sustainable development. Contemporary societies are structured in a way that is conducive to the accumulation of people in conurbations. This tendency is becoming stronger over the years (UN, 2015). The rising concentration of dwellers in cities around the world comes with changes in land use, ecosystems and environmental quality (UN, 2015). Continuous growth of the building sector, which directly accounted for a 3% increase in the entire yearly anthropogenic greenhouse gas emissions between 2000 and 2010, along with other energy consuming human activities significantly contributes to climate change (IPCC, 2014). Major complications are not only the increase of cities' ambient temperature, which consequently exacerbates energy consumption patterns, lowers amenity standards and sets impediments to economic performance, but also more intensive and unexpected rainfall events leading to urban flood incidents (IPCC, 2014). In order to protect against the deterioration of citizens' well-being, many techniques can be employed, with green roofs being one of them (Jim, 2017). The following analysis focuses on the energy conservation achieved by green roof technology, since water run-off management is a complicated issue that requires dedicated examination in separate research.

Green roofs improve the energy performance of buildings because they provide higher thermal inertia, shading and absorption of solar energy by the plants, and evapotranspiration cooling effects (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014). Recent research confirms the favorable contribution of this particular technology to improved energy use patterns. For example, the thermal performance of two tall buildings located in Hong Kong was examined under various weather conditions and building thermal insulation (BTI) scenarios, either by identifying the heat flow entering and exiting the building using a coupled green-building roof system (Jim, 2015), or by measuring air-conditioning energy consumption in situ (Jim, 2014). Both studies conclude that green roofs have positive contribution on the thermal mass enhancement, bring notable reduction in cooling loads, and increase energy savings.

Experimental results have also highlighted the positive effect of green roofs to building energy efficiency. For instance, Pandey, Hindoliya, & Mod (2012) proved that the green roof decreases the design cooling capacity up to 1.25 kW in a regular summer day in Ujjain, India, while Theodosiou, Aravantinos, & Tsikaloudaki (2014) confirmed a temperature reduction under the examined green roof's bitumen coating close to 25 °C in comparison with an ordinary roof formation and under Mediterranean climatic conditions. Furthermore, case-study approaches were adopted to allow a deeper insight into the thermal behavior of an experimental building in Guangzhou, China (Yang et al., 2015), a three-story building in Iran (Refahi and Talkhabi, 2015) and a representative four-story building in Amman, Jordan (Goussous, Siam and Alzoubi, 2015). All three studies indicated that particularly in hot climates, green roofs are quite advantageous in reducing energy consumption, with energy savings ranging from 6.6% to 17%.

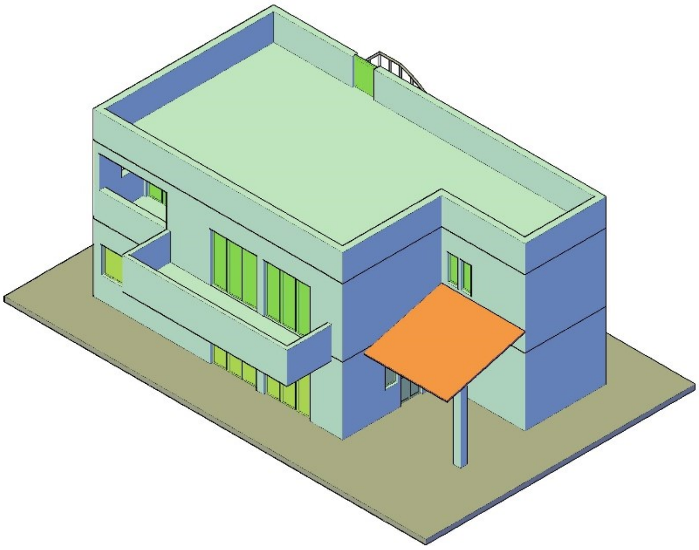
Urban microclimate mitigation by the green roofs is also an important aspect considered by recent studies. For example, Berardi (2016) confirmed the positive effects of green roofs both on building energy needs (i.e. energy demand reduction by 3%) and on pedestrians' thermal comfort (i.e. diurnal air temperature reduction of the order of 0.4 °C at pedestrian level). According to Alcazar, Olivieri, & Neila (2016) the combination of green roofs with greenery at pedestrian level can enhance the benefit on the surrounding microclimate with ambient temperature decline up to 2 °C. In contrast with these findings, Vuckovic, Kiesel, & Mahdavi (2017) claim that green roofs do not seem to significantly affect ambient temperature in the urban canyon, but they might be important for better thermal performance of individual buildings. In any case, local climatic conditions, construction types of green roofs (i.e. intensive, extensive, and semi-intensive systems), and spatial planning are key for the microclimatic efficiency of this retrofit option (Morakinyo et al., 2017).

Adding to earlier analysis of Ziogou et al. (2017), which focused on buildings of the tertiary sector, this study provides a holistic evaluation of the positive contribution of green roof technology to urban residential conditions of the Mediterranean island of Cyprus. The energy, environmental and economic aspects related to the application of green roofs to a typical two-story single-family building and a typical four-story multi-family one in four major cities (Nicosia, Larnaca, Limassol, and Paphos) are examined. Apart from simulating different types of buildings, this chapter includes two aspects that had not been considered in the aforementioned study. Firstly, a sensitivity analysis was conducted in an effort to investigate the impact of different monetary variables on the economic evaluation of this nature-based solution and explore the potential of turning it into a more enticing investment. Moreover, the scope of the research is expanded from the individual building perspective to a characteristic neighborhood scale implementation in order to assess the impact of green roofs on the Urban Heat Island (UHI) mitigation.

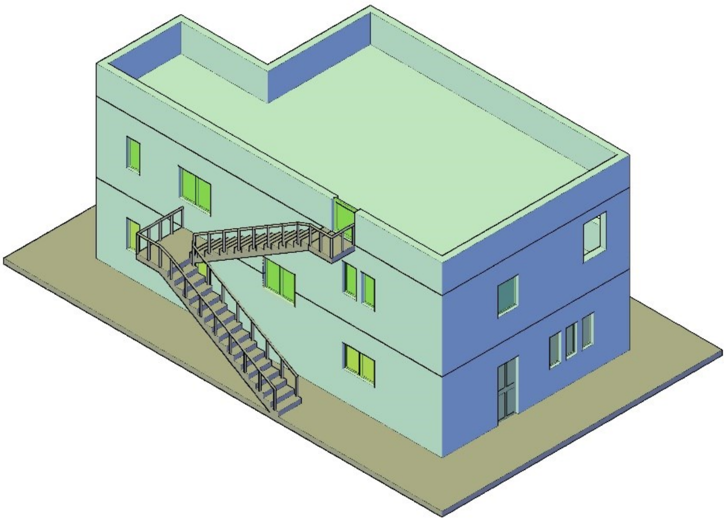
3.2 Description of the typical residential buildings and climate characteristics of the study area

3.2.1 Description of the typical building envelopes

Two characteristic types of residential buildings commonly found nationwide (CYSTAT, 2015) are examined. The first one refers to a free-standing two-story single-family building (Figure 8) of an entire area of 204 m^2 whose ground floor plan consists of the sitting and dining room, the kitchen and a studying area and its first floor, internally connected with the ground floor by a stairway, comprises a sitting area and three bedrooms. The windows occupy around 15% of the whole façade surface, with 70% placed on the southern and 22% on the northern part of the building.



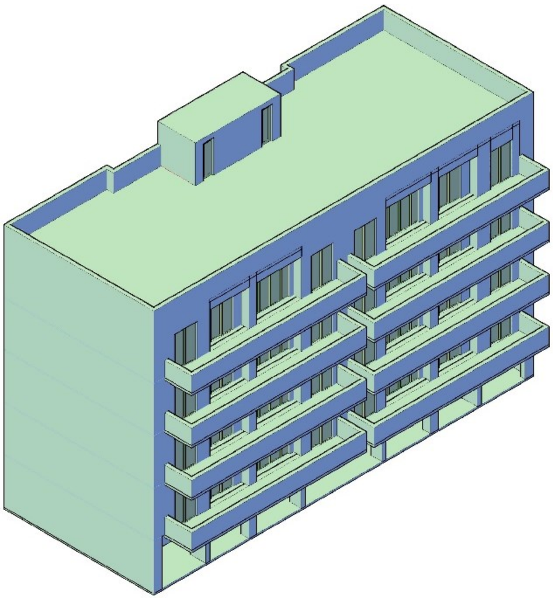
(a)



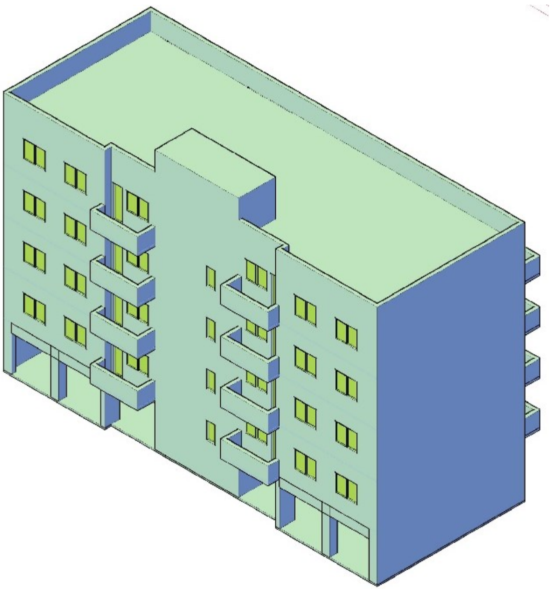
(b)

Figure 8: Panoramic view of the examined single-family building; South-East view *(a)* and North-West view *(b)*

The second one refers to a freestanding four-story multi-family building constructed over pilotis and is three-dimensionally depicted in Figure 9. Each typical floor comprises two independent residences, 113.3 m^2 each, besides the communal staircase area. Each residence includes a sitting room, a kitchen, a studying room and three bedrooms. The windows occupy around 17% of the whole façade surface and their majority (60%) is located on the southern part of the building.



(a)



(b)

Figure 9: Panoramic view of the examined multi-family building; South-West view *(a)* and North-West view *(b)*

Buildings in Cyprus are mainly reinforced concrete constructions with flat roofs. Regarding the thermal insulation conditions, there are two cases found: a) no thermal insulation is applied (mainly in buildings before 2007); b) extruded polystyrene (XPS) layer is placed on the horizontal and vertical elements of the frame and the masonry (mainly in buildings after 2007) (CYSTAT, 2015). Both insulation typologies are considered in the analysis scenarios, in order to comprehensively examine the existing architectural features of the housing stock in Cyprus. For the first case -uninsulated buildings-, the thermal transmittance (U) values of the horizontal structural components, the vertical external concrete elements, and the external masonry are 3.28, 3.56, and 1.39 W/(m^2·K) respectively. For the second case -insulated buildings-, these values are equal to 0.61, 0.62, and 0.52 W/(m^2·K) respectively. In all cases, windows are equipped with aluminum frame and double glazing whose thermal transmittance values are 2.98 W/(m^2·K) and 2.8 W/(m^2·K), respectively.

The selection of the construction elements in both reference building typologies and construction periods has been fully based on the current and past construction practices of the island, while their thermal transmittance values have been calculated in compliance with the Cypriot legislation regarding the energy performance of buildings (Republic of Cyprus, 2015b). In the framework of this study and in order to examine the common cases in which a green roof can be applied on new or renovated residential plots, we have considered uninsulated and perimetrically insulated buildings with either ordinary or two different green roofs that are described in Section 2.2 below.

3.2.2 Green roof configuration

Among the two dominant green roof typologies, the extensive and intensive ones, the former has been chosen for the purposes of this study mainly due to its shallow soil layer and consequently minimal static stress to the buildings' load bearing structure, and its confined installation costs and maintenance needs (Vijayaraghavan, 2016). The selected construction materials meet certain qualitative criteria that are important for promoting the sustainability of the proposed green roof formations. For example, for the two selected extensive green roof formations, native Mediterranean plants, i.e. *Helichrysum Orientale* (aromatic xerophyte) and *Sedum Sediforme* (succulent plant), have been chosen to separately form the two vegetation coverings because of their inherent ability to withstand adverse local climatic conditions (Butler, Butler and Orians, 2012). Furthermore, recycling products, i.e. compost in the soil mixture and rubber crumbs as a drainage layer, have been selected not only for their environmental contribution but also for their advanced physical properties (Hill, Drake, & Sleep, 2016; Pérez et al., 2012). More details regarding the formation of the two proposed alternative rooftop retrofit options are included in Table 1 of Section 3.1 and Ziogou et al. (2017).

3.2.3 Neighborhood design

The impact of the wider implementation of green roof retrofits on the urban microclimate with respect to local prevailing urban planning conditions was examined using an existing representative neighborhood in Limassol. The selected urban formation, whose three-dimensional geometrical domain is presented in Figure 10, consists of both multi-family buildings and single-family ones that are grouped into blocks and are separated by asphalt roads. The size of the domain area is 197.5 m × 120.0 m. Both building types found in this area have the same construction characteristics with the typical ones used in our analysis. In addition, the ground formation consisting of asphalt roads, concrete pavements, exposed soil and limited grass coverage has been extracted from the actual urban figure and is represented by the black, grey, orange and green colored areas of Figure 10, respectively.

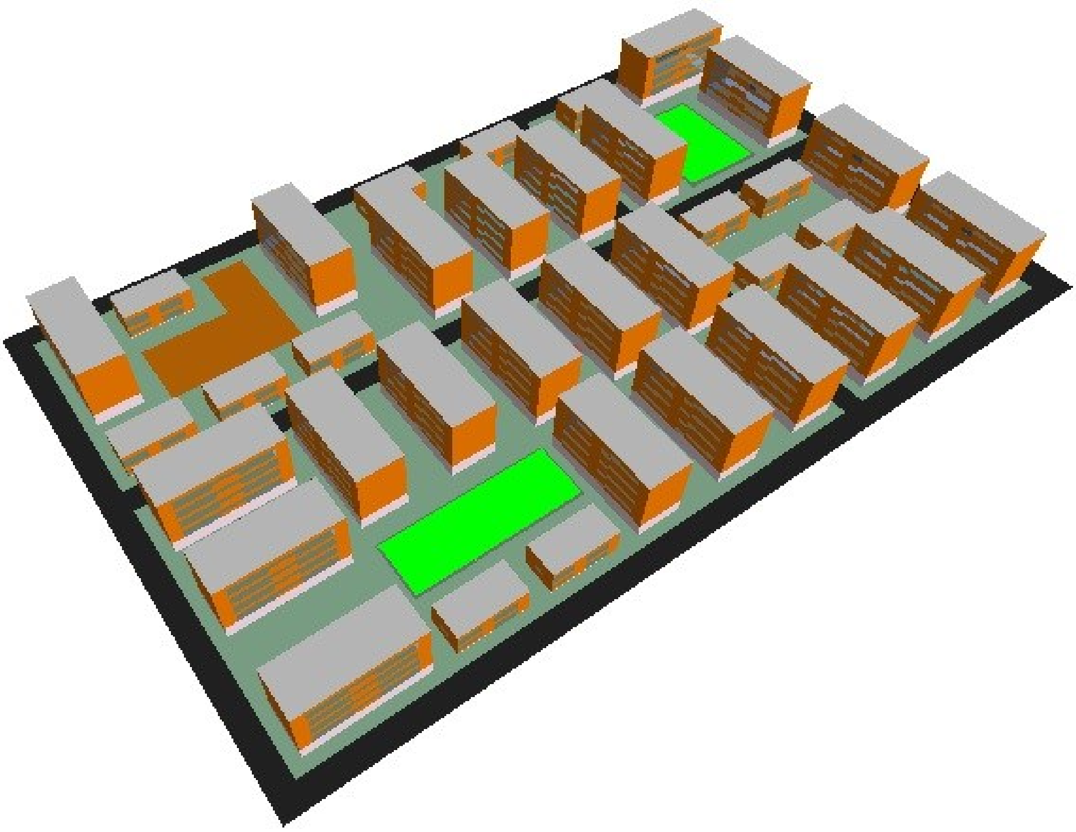


Figure 10: 3D view of the examined residential area used in UHI analysis.

3.2.4 Climatic characteristics

The climate of Cyprus (latitude 35° north, longitude 33° east) is characterized by hot dry summers from mid-May to mid-September, and rainy, pretty variable, winters from November to mid-March that are separated by short autumn and spring seasons of swift alteration in weather conditions (Republic of Cyprus; Department of Meteorology, 2017). Regarding the examined regions, Nicosia, the capital city of Cyprus, presents the coldest climate of the study area as the heating degree days ($HDD_{20/12}$) are equal to 441 Kdays, according to the METEONORM meteorological database (Meteotest AG, 2017). In addition, Limassol, the second largest city of the island, is the hottest in the region with 221 Kdays. Moreover, Larnaca and Paphos having 340 Kdays and 223 Kdays respectively, represent the intermediate and the hot climate of the country.

3.3 Description of simulation software and algorithms, and data analysis

3.3.1 Simulation of the buildings' envelopes

The energy analysis of the building envelopes was conducted using the EnergyPlus simulation software which is appropriate for dynamically modelling the heating and cooling energy needs of buildings (DOE. Department of Energy; US, 2017). For this purpose, 12 and 45 separate thermal zones were assigned to the single-family building and multi-family one, respectively. Following the inhabitants' common habits in the study area, the usage profiles of the interior spaces and the associated thermal comfort parameters were formulated on a daily, weekly and monthly base, considering continuous building operation all around the year. In addition, and in order to be more accurate and realistic, the daily usage profiles were divided into two separate periods. The first period starts at 07:00 and finalizes at 22:00, representing the high operation hours of the day. Moreover, a second low operation period, between 23:00 and 6:00, was considered, during which the cooling, heating, lighting and electrical equipment energy needs are substantially decreased. The required temperature distribution during the high and low operation period for the heating and cooling process are set at 22 °C/18 °C and 25 °C/30 °C, respectively (CEN, 2007; ASHRAE, 2013). In addition, the daily rate of air changes is set at 0.8 ach (CEN, 2007; ASHRAE,

2013) and the lighting levels are equal to 6 W/m^2 (3.5 W/m^2 for WC) (ASHRAE, 2013; adapted from CEN, 2007).

The energy analysis of the green roofs was performed using again EnergyPlus software and more specifically the EcoRoof model that is incorporated in the program's simulation core. The parameters of the two alternative rooftop retrofit options' simulation are gathered in Table 5. The height of plants, the minimum stomatal resistance, the leaf area index, and the thickness of the substrate are major influencers regarding the green roofs' energy efficiency (Refahi and Talkhabi, 2015; Costanzo, Evola and Marletta, 2016; Silva, Gomes and Silva, 2016). Therefore, there are intentionally distinct differences in the values regarding the two alternative formations. Both cases of either the presence or the lack of irrigation of Helichrysum Orientale or Sedum Sediforme, respectively, rely on previously established experimental results that confirm the endurance of these species under extended dry periods (Nektarios et al., 2014; Papafotiou et al., 2013). Last but not least, the required climatological data are extracted from the METEONORM's meteorological database.

Table 5: EcoRoof Model parameters for both cases of selected plant cover (Ziogou *et al.*, 2017)**.**

		Helichrysum Orientale L. (Green Roof 1 / GR1)			Sedum Sediforme (Green roof 2 / GR2)	
Category	Field	Unit	Value	Reference	Value	Reference
Vegetation	Height of plants	m	0.15	(Papafotiou *et al.*, 2013)	0.25	(Nektarios *et al.*, 2014)
	Leaf area index	-	3.50	(Varras et al., 2015)	1.75	(Nektarios *et al.*, 2014)
	Minimum stomatal resistance	s/m	125.00	(Kokkinou et al., 2016)	300.00	(Tabares-Velasco and Srebric, 2012)
Growing medium	Thickness	m	0.075	(Papafotiou *et al.*, 2013)	0.15	(Nektarios *et al.*, 2014)
	Conductivity of dry soil	W/(m·K)	0.20	(Sailor, Hutchinson and Bokovoy, 2008)	0.20	(Sailor, Hutchinson and Bokovoy, 2008)
	Density of dry soil	kg/m^3	1020.00	(Sailor, Hutchinson and Bokovoy, 2008)	1020.00	(Sailor, Hutchinson and Bokovoy, 2008)
	Specific heat of dry soil	J/(kg·K)	1093.00	(Sailor, Hutchinson and Bokovoy, 2008)	1093.00	(Sailor, Hutchinson and Bokovoy, 2008)
	Thermal absorptance	-	0.96	(Sailor, Hutchinson and Bokovoy, 2008)	0.96	(Sailor, Hutchinson and Bokovoy, 2008)
	Solar absorptance	-	0.85	(Sailor, Hutchinson and Bokovoy, 2008)	0.83	(Sailor, Hutchinson and Bokovoy, 2008)
	Saturation Volumetric Moisture Content of the Soil Layer	-	0.26	(Sailor, Hutchinson and Bokovoy, 2008)	0.13	(Sailor, Hutchinson and Bokovoy, 2008)
Irrigation	Irrigation Rate Schedule Name	l/h	3.30	(Papafotiou *et al.*, 2013; Van Mechelen, Dutoit and Hermy, 2015)	*No irrigation*	(Nektarios *et al.*, 2014)

3.3.2 Energy analysis of the heating and cooling system

The selected system for maintaining the required indoor conditions on heating and cooling period of the typical buildings took into consideration the recent market trends and customers' preferences on new and renovated dwellings. Based on that, a local heating and cooling system consisting of a variable speed split type air-to-air heat pump is considered in all cases. It is worth mentioning that although a local system is not favorable in terms of energy performance compared to the central one, it is selected in the frame of this study in order to simulate the existing construction practice of the study area.

The final energy consumption of the buildings' envelopes was calculated through a dynamic simulation procedure incorporated in an in-house developed model. More specifically, the buildings' heating and cooling energy demand, and the ambient air temperature were used as input parameters. Then, based on characteristic curves of the coefficient of performance or the energy efficiency ratio which were extracted from the engineering data book of the manufacturer (TOSHIBA, 2017) and are dependent on the hourly values of the ambient air temperature and the heat pump's load, the electricity consumption of the equipment was calculated.

3.3.3 Environmental analysis of the alternative rooftop retrofit options

For a quantitative comparison between the conventional individual buildings and the alternative ones with extensive green roofs with regard to their environmental impact, the emissions of CO_2, NO_x and SO_2 were calculated. To achieve this, the electricity consumption, resulting from the energy analysis of the heating and cooling system, was transformed into primary energy consumption, using the established national conversion factor that is equal to 2.7 kWh_{pr}/kWh_{el} (Republic of Cyprus, 2015a). Consequently, carbon dioxide emissions were calculated using the primary energy consumption through the established CO_2 emission factor (0.794) that is highly indicative of the fuel mix used in the national electricity production and provides the kilograms of released CO_2 per kWh of consumed primary energy (Republic of Cyprus, 2015a).

The emissions of the remaining local pollutants, i.e. NO_x and SO_2, are associated with the electricity produced in Cyprus according to Zachariadis & Hadjikyriakou (2016). Based on their analysis, the emission factors of the first and second pollutant are 1.29 and 3.94 tons of NO_x and SO_2 per GWh of the electricity production of power plants, respectively. The electricity consumption of the typical buildings that resulted from the analysis of the heating and cooling system was firstly converted to equivalent electricity production of the power plants by assuming transmission and distribution losses of 10.6% in line with recent evidence (EAC, 2015). Then, using the equivalent electricity production of power plants and the aforementioned emission factors, the emissions of these local pollutants were calculated on an annual basis.

3.3.4 Economic analysis of the alternative rooftop retrofit options

3.3.4.1 Economic feasibility

The economic evaluation of the extensive green roof solutions was performed using the Life Cycle Cost Analysis (LCCA) index, considering an economic lifespan of 30 years (EC, 2012). To address the social perspective, the analysis includes an assessment of changes in economic welfare due to the avoided environmental deterioration. Therefore, not only the operational costs but also the environmental costs of the emissions were incorporated in the calculation of the alternative rooftop retrofit options' Life Cycle Cost (LCC), as shown in the following equation.

$$LCC = -C_{in} - \sum_{j=1}^{n} \frac{EC \cdot C_{el,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{WC \cdot C_{w,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{C_{m,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{E_{CO_2} \cdot C_{CO_2,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{E_{SO_2} \cdot C_{SO_2,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{E_{NO_x} \cdot C_{NO_x,j}}{(1+d)^j}$$

C_{in} stands for the initial construction cost of the green roofs [€]. *EC* is the electricity consumption per year of the selected heating/cooling system [kWh_{el}/a] and $C_{el}j$ is the electricity cost for the *j*-year [€/kWh_{el}]. *WC* is the water consumption per year of the green roof system for irrigation purposes [m^3/a] and $C_{w}j$ is the water cost for the *j*-year [€/m^3]. $C_{m,j}$ represents the cost of maintenance works in *j*-year [€/a]. Moreover, E_{CO_2}, E_{SO_2}, and E_{NO_x} stand for the annual emissions of the indicated substances [kg/a], respectively, and $C_{CO_2,j}$, $C_{SO_2,j}$, and $C_{NO_x,j}$ refer to the annual cost per mass of emitted substances [€/kg], respectively. Finally, *d* is the discount rate [%] that reflects the social perspective, and *j* represents the calculation's year. The formula has been validated in the following publication: I. Ziogou, A. Michopoulos, V. Voulgari, T. Zachariadis, Implementation of green roof technology in residential buildings and neighborhoods of Cyprus, Sustainable Cities and Society 40 (2018) 233–243.

According to the information provided by the private company kartECO, the installation costs of the green roofs were estimated at the level of 8,330 € and 18,700 €, as of January 2017, for the single-family and multi-family building, respectively. Moreover, the maintenance cost was set equal to 3.5% of the installation cost, considering reasonable local present and forthcoming market prices. In addition, for the calculation of the yearly electricity cost, projections of the Energy Ministry of Cyprus of March 2017 were used for the 30-year period up to 2046[5]. Finally, the environmental costs per emission weight were extracted from the existing literature and appropriately adjusted to the economic conditions of Cyprus, as explained by Zachariadis & Hadjikyriakou (2016). All values are given at constant prices of year 2015. A social real discount rate of 4% was used, according to guidance provided to the government of Cyprus by the World Bank (World Bank, 2016) and in line with the broader relevant literature (Steinbach and Staniaszek, 2015), since the assessment focuses on the social perspective rather than the individual preferences of private investors.

3.3.4.2 Sensitivity analysis

In order to investigate the sensitivity of these calculations to the most uncertain parameters, we recalculated the LCCs of the extensive green roof systems assuming a range of possible investment costs and different future electricity costs. More specifically, we allowed the above-mentioned installation cost of 8,330 € and 18,700 € for the single-family and multi-family building respectively, to decrease by up to 40%, assuming cost improvements due to technological progress or learning-by-doing as the number of such installations increases in the future.

As regards electricity costs, apart from the baseline price scenario that is used in the calculations described in section 3.3.4.1, we assumed two additional scenarios reflecting a higher and a lower trajectory of electricity prices in the future. The low price scenario follows an unpublished "Reference" forecast of the Energy Ministry of Cyprus (see footnote 1), while the high price scenario follows the trend of the "Current Policies

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[5] This is an unpublished forecast made by energy authorities assuming that no natural gas will be used in power plants in the future ("No gas scenario"); it was obtained through personal communication with the Energy Ministry of Cyprus.

Scenario" from the latest World Energy Outlook of the International Energy Agency (IEA, 2016).

In short, while the baseline price scenario assumes retail electricity prices to remain close to today's levels and essentially constant in real terms (around 18 Eurocents'2015/kWh) up to the mid-2040s, the low price scenario assumes real electricity prices to fall slightly to 16-17 Eurocents'2015/kWh due to the introduction of natural gas in the power system of Cyprus; and according to the high price scenario, which assumes higher international oil and gas prices, retail electricity prices rise gradually up to 22 Eurocents'2015/kWh in the mid-2040s.

3.3.5 Simulation at the neighborhood scale

The environmental analysis for the selected residential neighborhood was conducted using ENVI-met software (version 4.3.0), an integrated three-dimensional non-hydrostatic model, simulating the interactions between natural and artificial surfaces, vegetation, and air layers (ENVI_MET GmbH, 2017b). The model calculations indicatively involve shortwave and longwave radiation interactions with vertical, horizontal and declined building components and urban vegetation, as well as the evapotranspiration and thermal procedures of plants considering all their physical parameters including photosynthesis rates, with the common calculation time ranging from 24 to 48 hours (ENVI_MET GmbH, 2017b).

Earlier studies have already used this software in order to investigate the improvement potential of urban microclimatic conditions and have confirmed its reliability. The validity of the ENVI-met model has been proven through the high correlation between simulated data and measured ones (Berardi, 2016), low percentage deviation among the recorded and the simulated ambient temperature and humidity ratios (Battista, Carnielo and De Lieto Vollaro, 2016), and low root mean square error values between the ENVI-met modelled and the experimentally observed air temperature (Jamei and Rajagopalan, 2017). The configuration details of the three-dimensional geometrical model along with the simulation parameters used in our analysis are presented in Table 6.

Table 6: ENVI-met model parameters.

Field	Value	Explanatory comment
Main model area	79 × 48 × 30	Number of grids
Grid size	2.50 m × 2.50 m × 1.00 m	Sufficient spatial resolution
Nesting grids around main area	3	In order to avoid boundary effects
Start simulation day	21/07/2017	Hottest day of the year for the selected location
Start simulation time	06:00	In order for the calculations to be in line with the atmospheric procedures
Total simulation hours	24 h	Minimum required duration is 6 hours in order to prevent undesired effects (possibly caused by the transitory conditions in the initialization phase of the simulation) (ENVI_MET GmbH, 2017a)
Wind speed in 10m above ground	1.32	Average value
Wind direction	189.89	The rotation of the modelled area (26.56° to the right) has been taken under consideration
Roughness Length z0 at Reference Point	0.01	Urban environment

Meteorology inputs	Temperature and relative humidity	Simple forcing was used, and the data were extracted from the METEONORM weather files
Adjustment factor for shortwave solar radiation	0.82	Solar energy fluxes estimated by the internal method of ENVI-met are higher than the ones given by the METONORM weather files
Building and green roof properties	Similar to the ones used in EnergyPlus simulations	

3.4 Results and discussion

3.4.1 Energy assessment

The primary energy consumption index (kWh/m^2) was herein utilized since it is a widely accepted energy efficiency indicator. The corresponding values during the heating and cooling operation and the percentage differences among the selected conventional flat roof and the corresponding alternative extensive green ones, for both insulated and uninsulated buildings, are provided in Figures 11-14.

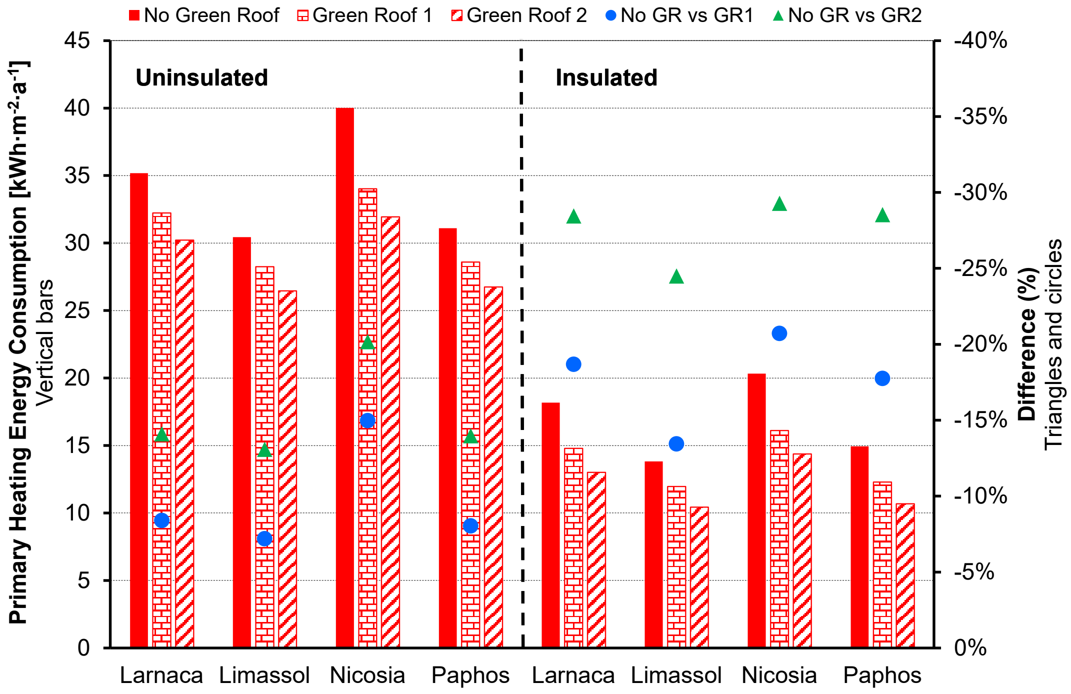

Figure 11: Primary energy consumption of the single-family building during the heating period.

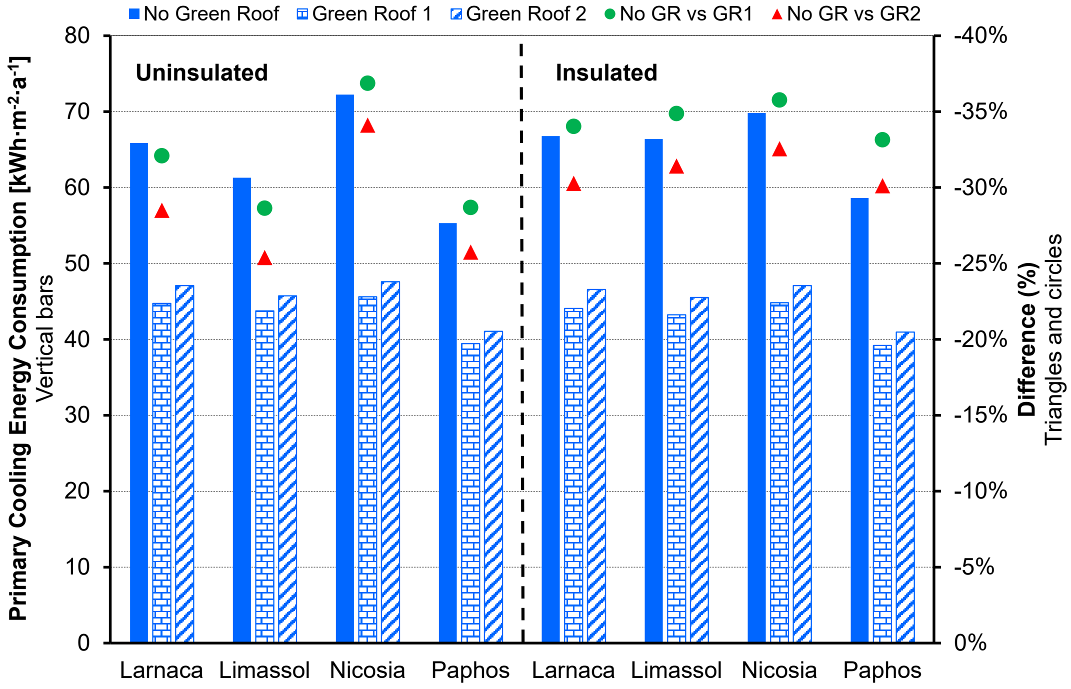

Figure 12: Primary energy consumption of the single-family building during the cooling period.

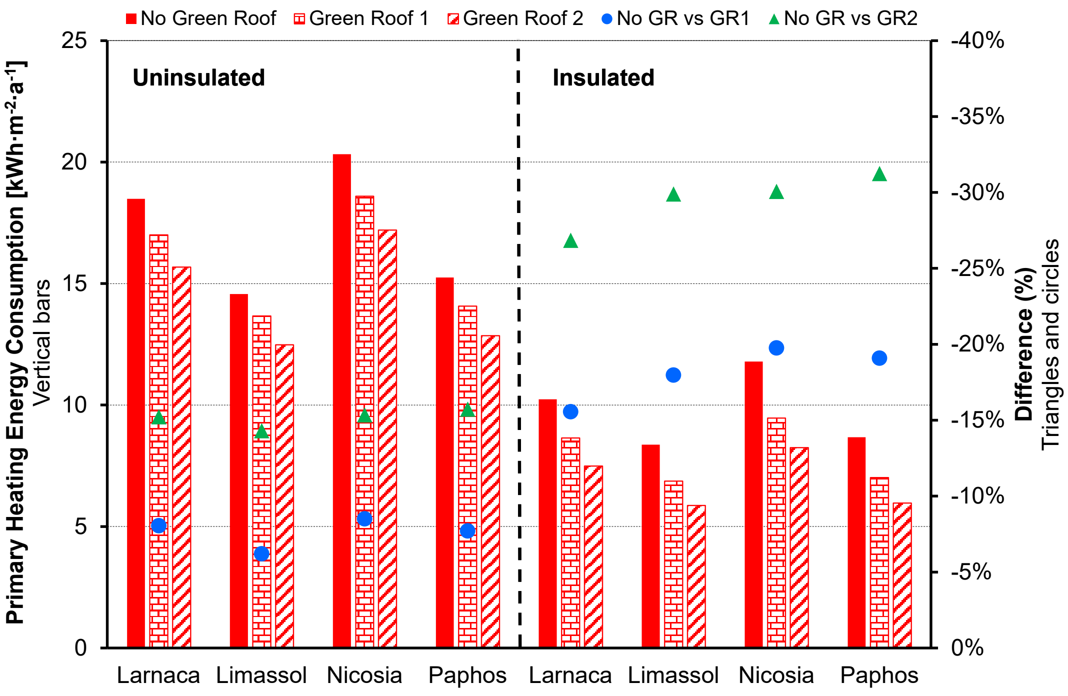

Figure 13: Primary energy consumption of the multi-family building during the heating period.

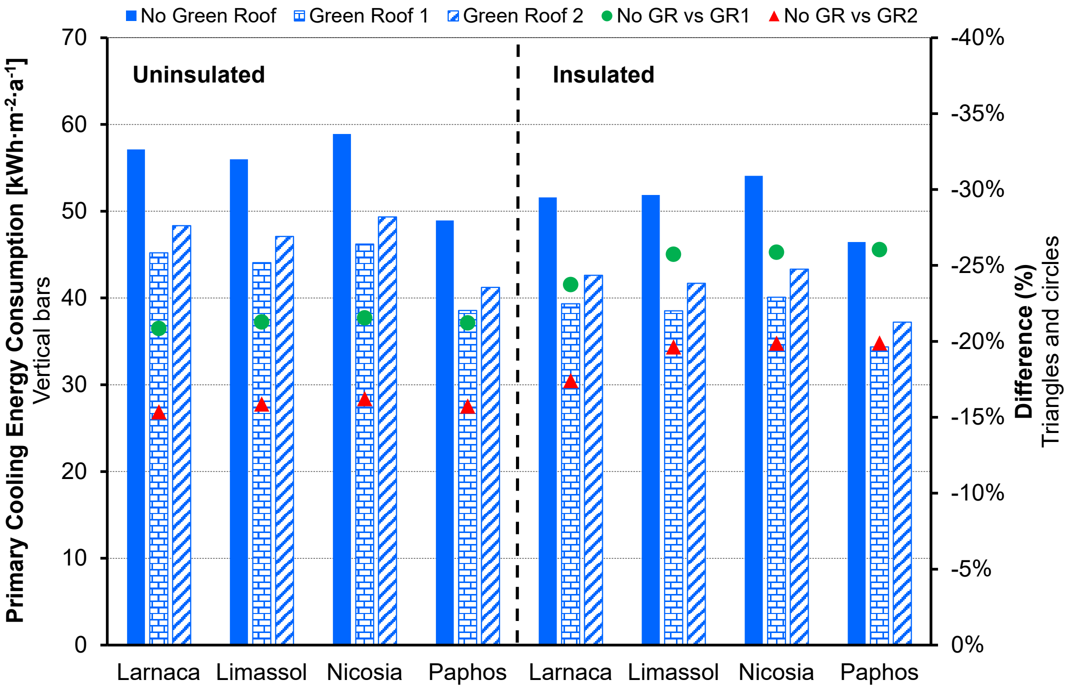

Figure 14: Primary energy consumption of the multi-family building during the cooling period.

What stands out in the figures is that the highest reduction in primary energy consumption for heating purposes (almost 30%) is achieved by the extensive green roof configuration with the second vegetation covering for both types of buildings and insulation’s application. On the contrary, the highest energy savings under the summer operation of the examined building types are accomplished when the extensive green roof configuration with the first plant option is applied, with energy savings well over 35% and 25% for the single-family and multi-family buildings respectively.

Regarding the uninsulated single-family buildings, the highest overall primary energy savings for heating and cooling (equal to 29%) are observed in the case of Nicosia which is the coldest region. A lower reduction - hardly exceeding 23% - is achieved in the remaining cities. In the insulated cases of single-family buildings, the overall primary energy reduction for heating and cooling is almost stable at 30% to 32%. These results apply to both types of alternative rooftop retrofit options.

With regard to multi-family buildings and for all cities under consideration, the extensive green roof with the first plant alternative offers the highest overall primary energy savings for heating and cooling of the order of 18% and 24% for uninsulated and insulated buildings, respectively. The corresponding reductions in the extensive green roof with the second vegetation type are 16% and 21% respectively. It is worth mentioning that the calculated energy savings are consistent among the different regions despite differences in their climatic characteristics.

3.4.2 Environmental evaluation

The ultimately reduced amounts of CO_2 emissions are presented in Figures 15 and 16. It is apparent from these figures that a similar significant annual reduction of the emitted amounts of CO_2 is achieved, when either of the two types of extensive green roofs is applied. This positive impact is more profound both in single- and multi-family building for the case of perimetrically applied insulation.

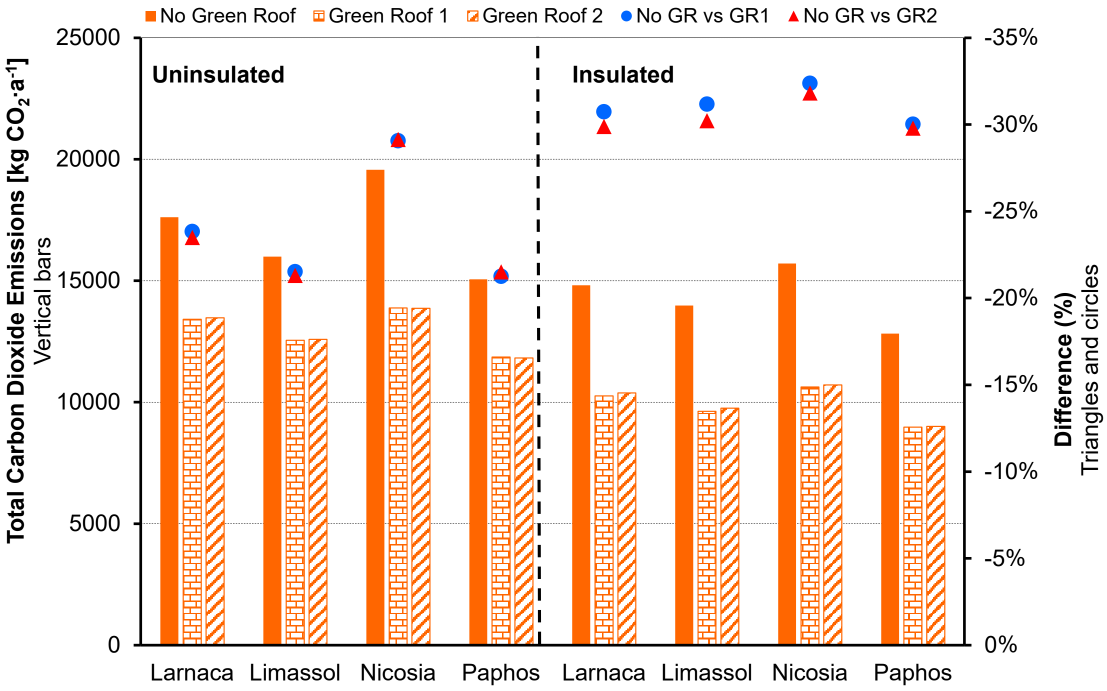

Figure 15: Total CO_2 emissions produced under the annual operation of the single-family building.

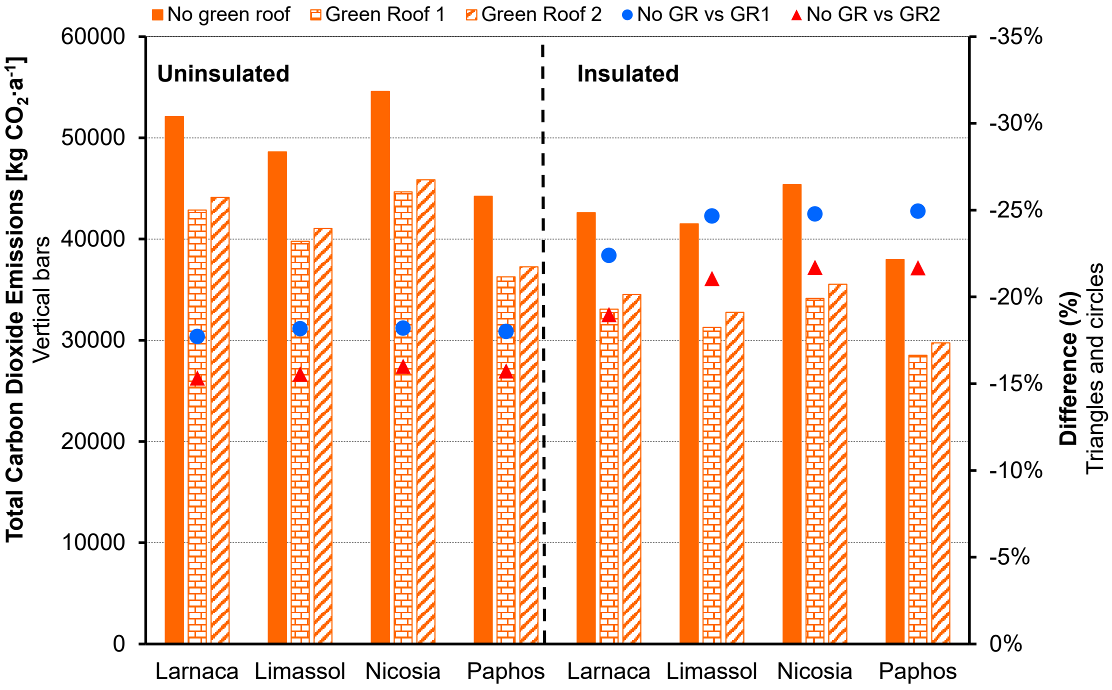

Figure 16: Total CO_2 emissions produced under the annual operation of the multi-family building.

The indirect annual emissions of the remaining local pollutants are illustrated in Figures 17-20.

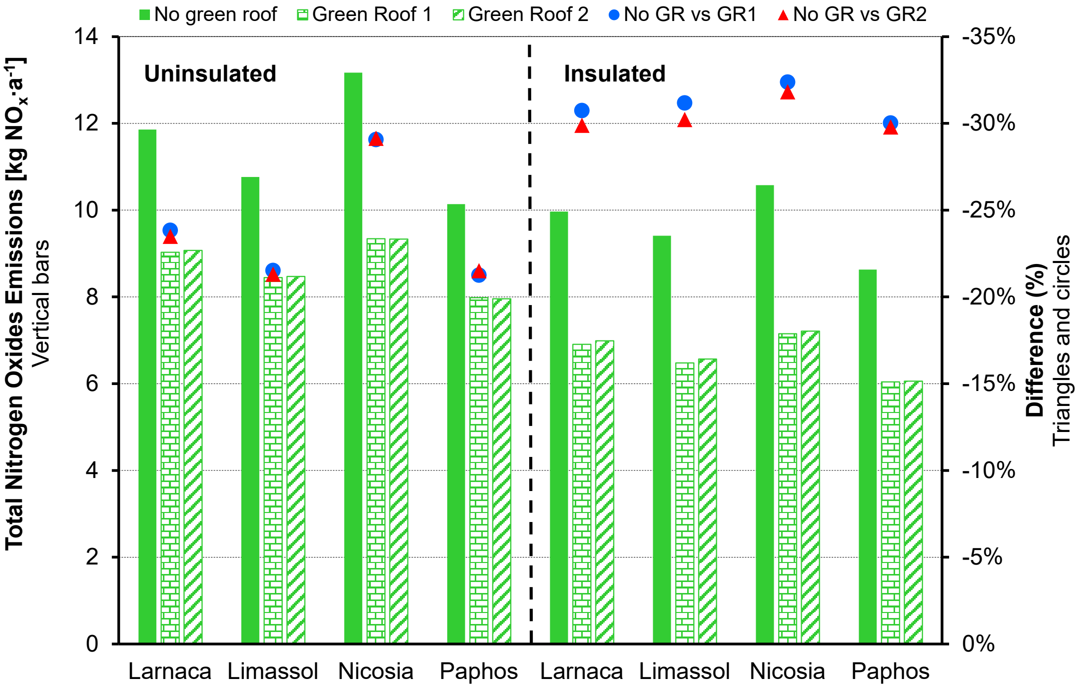

Figure 17: Total NO$_x$ emissions produced under the annual operation of the single-family building.

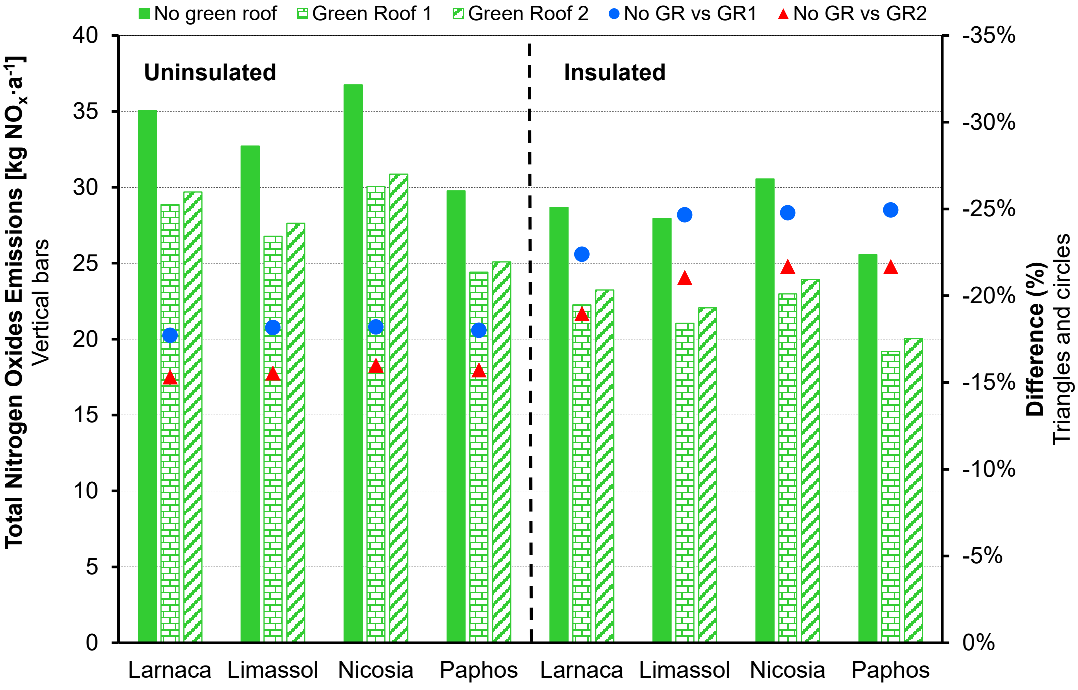

Figure 18: Total NO$_x$ emissions produced under the annual operation of the multi-family building.

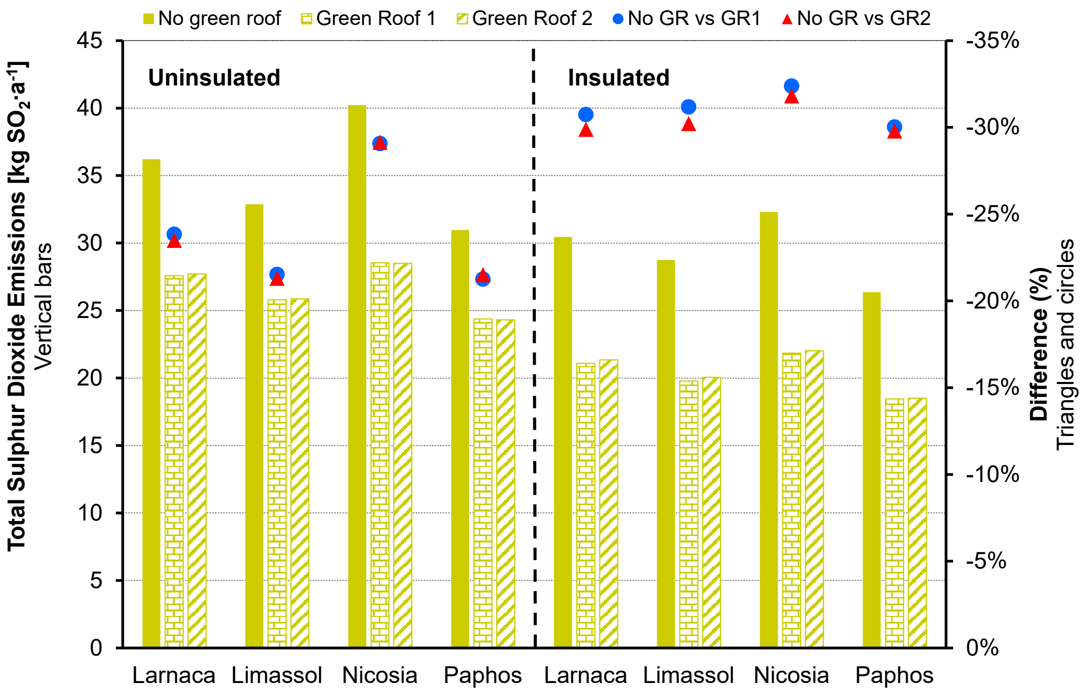

Figure 19: Total SO_2 emissions produced under the annual operation of the single-family building.

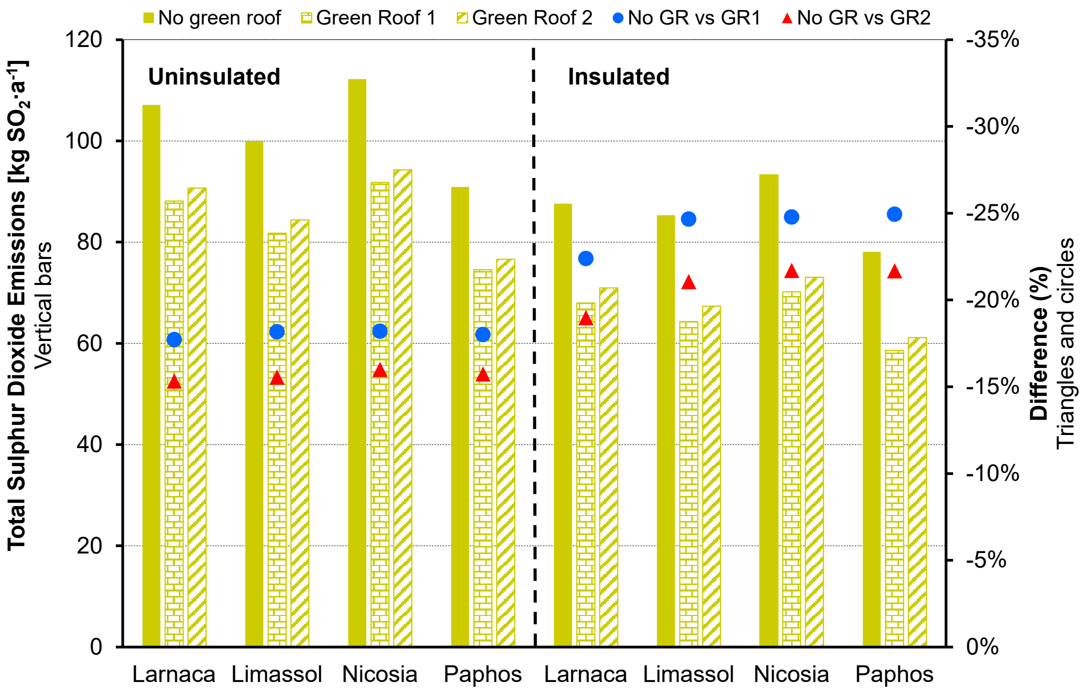

Figure 20: Total SO_2 emissions produced under the annual operation of the multi-family building.

The overall findings indicate that there is indeed an important reduction in NO_x and SO_2 emissions, regardless of the city in which either of the two extensive green roof configurations is applied. This reduction is stronger in single-family buildings. Both extensive green roof formations that are installed in single-family buildings seem to have a similar ameliorating impact on these local pollutant emissions, whereas in multi-family ones the first solution is environmentally more favorable (by roughly 2.4% and 3.3% in uninsulated and insulated cases respectively). The beneficial environmental impact of retrofitted roofs is more intensive in insulated buildings.

Still in absolute terms and compared to CO_2 emissions, emissions of local pollutants are relatively low. This figure can be attributed to the fuel mix in the electricity production in Cyprus (fuel oil, gas oil and renewable sources). The environmental improvements would clearly be higher in another country with a differentiated fuel mix (e.g., using coal-fired power plants), which would result in a more favorable evaluation of green roof technology.

3.4.3 Economic feasibility and sensitivity analysis

3.4.3.1 Economic feasibility

The resulting LCCs of the economic assessment are shown in Figures 21 and 22. They are quite higher (in absolute terms) than the ones of the conventional flat-roof residential buildings, especially in the case of the single-family building, where the increased additional cost of a green roof seems to be discouraging for such an investment (see also Tapsuwan et al., 2018). This additional cost derives mainly from the quite high initial installation expenses, and secondarily from green roof's maintenance and watering needs. An exception occurs for the city of Nicosia, where the proposed extensive green roof formations can provide a slight economic advantage, in the case of single-family buildings. Nevertheless, the general unfavorable trend could be reversed, if additional benefits, whose positive monetary contribution is hard to measure, were included in the economic analysis. These are conservation of local biodiversity (Bianchini and Hewage, 2012a), added property value due to the enhancement of the aesthetic quality (Lee et al., 2014), reduction of urban noise levels (Connelly and Hodgson, 2015) and protection against urban flooding thanks to the increased storm water retention capacity of the green roofs (Volder and Dvorak, 2014).

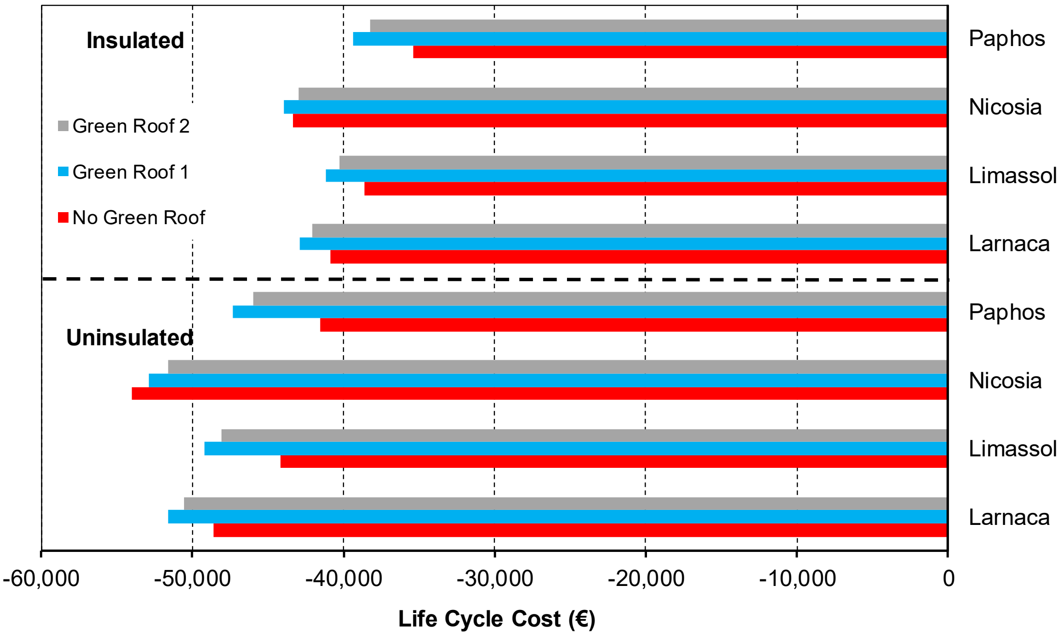

Figure 21: Life Cycle Cost of conventional and retrofitted roofs of single-family buildings for an economic lifetime of 30 years.

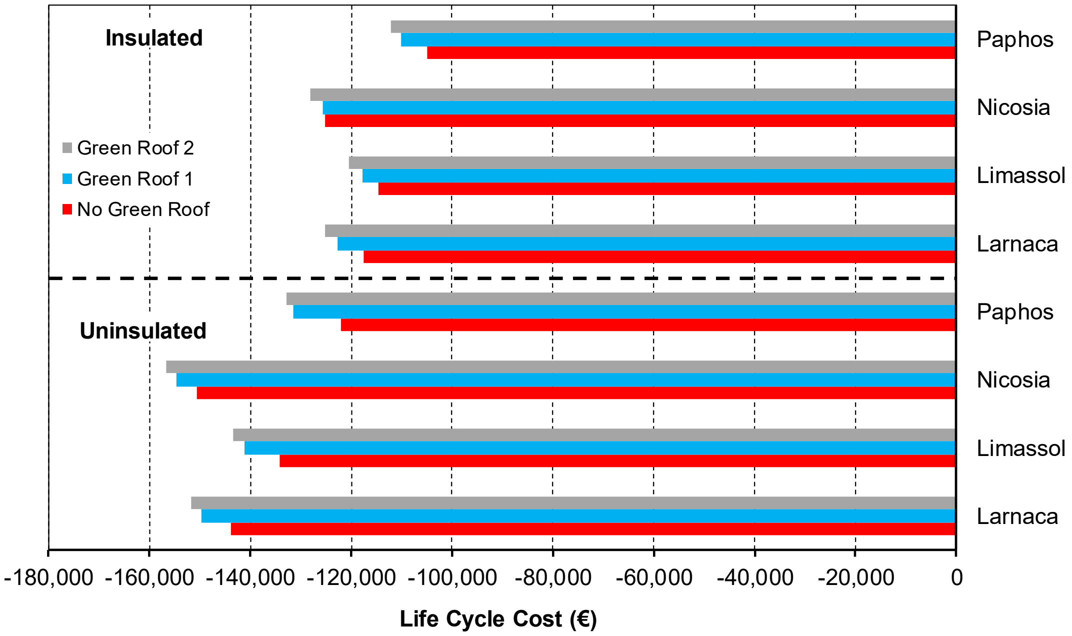

Figure 22: Life Cycle Cost of conventional and retrofitted roofs of multi-family buildings for an economic lifetime of 30 years.

3.4.3.2 Sensitivity analysis

As can be seen from Figure 22, the second extensive green roof (Sedum Sediforme plantation) presents the lowest LCC compared to its alternative, in the case of multi-family buildings. In addition, Paphos and Nicosia are the locations with the lowest and highest economic efficiency of green roofs, respectively, in terms of the difference between the LCCs of "Green Roof 2" and "No Green Roof" scenarios. Figures 23 and 24 show the results of this sensitivity analysis regarding the extensive green roof system with the second plant option in the cities of Nicosia and Paphos, for uninsulated and insulated multi-family buildings respectively. The relationship between the difference in NPVs of conventional and green roofs and the initial investment cost of green roofs is linear for all three electricity price scenarios. A positive value on the y-axis indicates that the LCC of the green roof system is greater than the LCC of the conventional building without green roof; in these cases, the building with green roof is financially more attractive than the conventional one. Evidently this comparison becomes more favorable for green roofs at higher electricity prices (which increases electricity cost savings) and lower green roof installation costs.

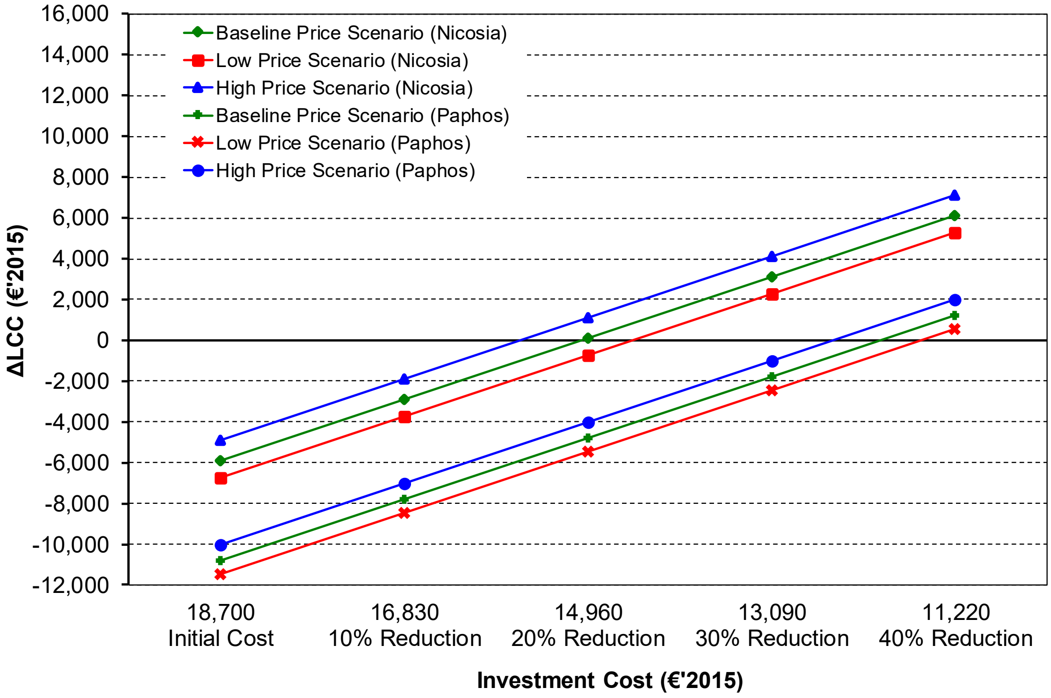

Figure 23: Sensitivity analysis of the extensive green roof system with the second plant option (Sedum Sediforme) for the uninsulated multi-family building in Nicosia and Paphos.

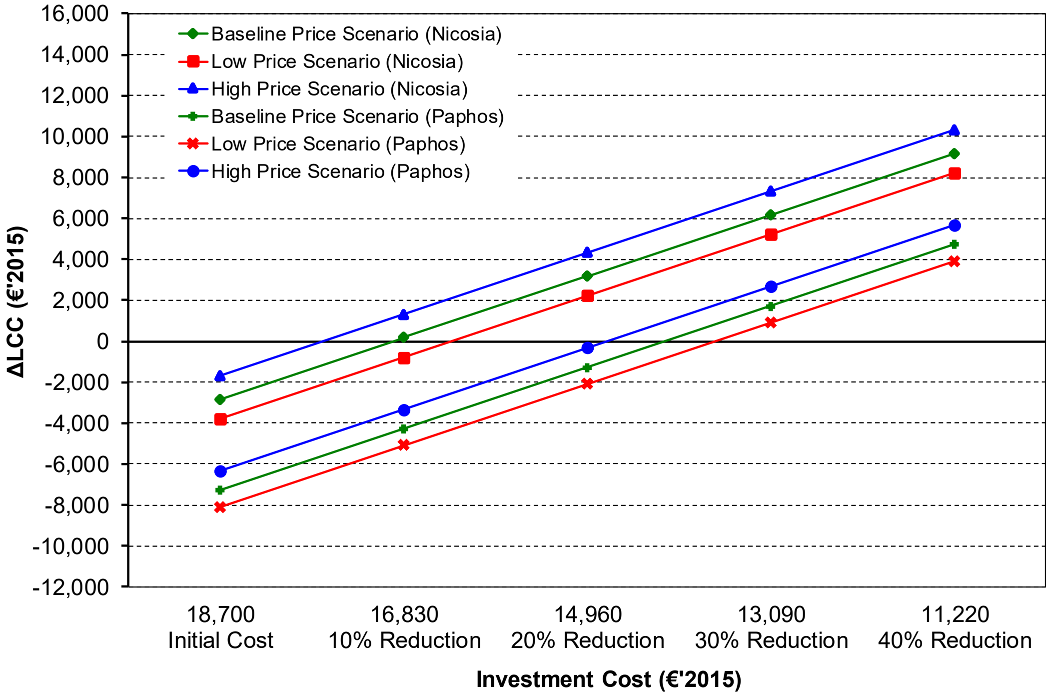

Figure 24: Sensitivity analysis of the extensive green roof system with the second plant option (Sedum Sediforme) for the insulated multi-family building in Nicosia and Paphos.

In the case of the most favorable location of Nicosia, modest improvements in investment costs, of the order of 6-22%, are sufficient for the green roof configuration to break even financially with the building without green roof. Adding the non-monetized benefits mentioned in section 4.3.1, this would yield a clearly favorable comparison for the green roof systems. However, even higher reduction rates than the ones already selected in the installation cost of the green roof are required for the investment to be cost-effective in the less favorable area of Paphos. Moreover, the improvement of the economic feasibility of the two alternative rooftop retrofit options on the non-illustrated areas of Limassol and Larnaca lies in between the aforementioned figures.

Similar results, yet slightly improved, were obtained from the sensitivity analysis of the extensive green roof with the first plant option in the multi-family building in all examined areas and under all the examined electricity price scenarios. With respect to single-family buildings and for the most disadvantageous city of Paphos, decreased investment costs varying from 18% up to 35% can turn the two proposed retrofit options into economically viable solutions. These results are not reported here for the sake of brevity but are available in the appendix. Again, one has to keep in mind the non-monetized benefits of green roofs that were mentioned in the previous section, which can substantially change the overall LCC result.

3.4.4 Impact on urban microclimatic conditions

The analysis has focused on air temperature differences at the pedestrian level on the neighborhood scale. Based on the percentage differences in the primary energy consumption between the flat roof buildings and the ones with green roofs, the location of Limassol and the case of perimetrically insulated residential buildings have been selected. Figures 25 and 26 present the spatial distribution of the numerical differences in air temperature between the base case scenario and the two alternative rooftop retrofit options (aromatic xerophyte and succulent plant) during the hottest hour of the summer design day.

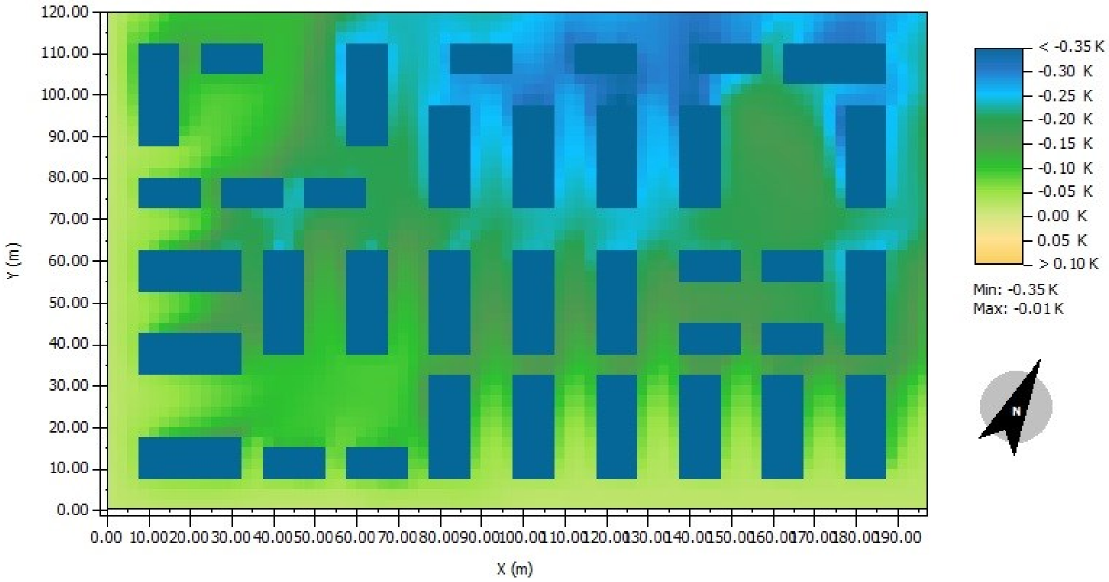

Figure 25: Numerical difference in air temperature between the conventional and first extensive green roof (Helichrysum Orientale) scenarios at z=1.50 m for the 21st of July at 16:00 pm.

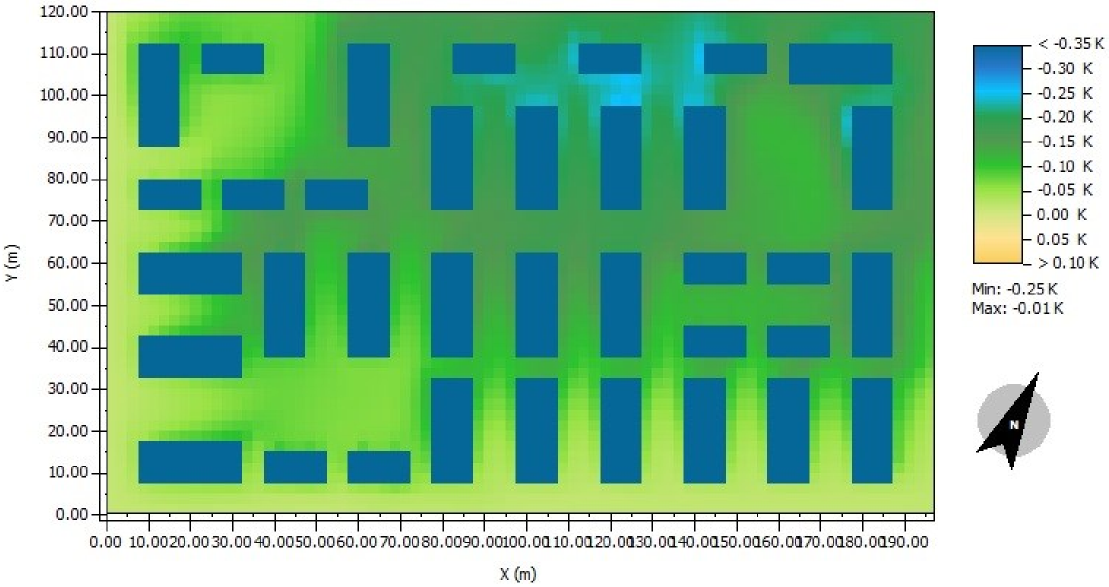

Figure 26: Numerical difference in air temperature between the conventional and second extensive green roof (Sedum Sediforme) scenarios at z=1.50 m for the 21st of July at 16:00 pm.

As can be seen from the figures above, the first type of the examined extensive green roofs yields more positive results since the cooling effect is 0.1 K higher than the one offered by the second type, following the same trend with the reduction in primary energy consumption of individual buildings as described in section 4.1. Generally, the decrease in air temperature at the selected height is apparent and starts to appear from the middle part up to the top right side of the examined area in consistence with the air direction.

Nevertheless, one should keep in mind that roof surface covers only about 20% of the entire urban surfaces; hence applying greenery in the remaining surface is highly recommended for stronger UHI mitigation (Morakinyo *et al.*, 2017). In addition, expanded application of green roofs at an even larger (e.g. district or city) scale would certainly have a clearer effect on the improvement of the urban micro-climate (Berardi, 2016).

3.5 Conclusions

This chapter has included a thorough evaluation of two alternative rooftop retrofit options (i.e., extensive green roofs with two different native plant solutions) for two dominant types of residential buildings in Cyprus. We have thus provided a comprehensive energy, environmental and economic analysis of these passive building design solutions combined with the examination of their contribution to the upgrade of urban micro-climatic conditions. The results of this study can be considered representative for the majority of Mediterranean areas since climatic characteristics, building regulations, and urban planning conditions in the region are broadly similar with the ones prevailing in Cyprus.

Despite the increased investment costs, shown in Fig. 21 and 22, we have confirmed the clearly positive energy and environmental contribution of green roofs. Indicatively, primary energy savings on heating mode can reach 30% for both building typologies, while under summer operation 35% and 25% reductions in primary energy consumption are found, for the considered single-family and multi-family buildings, respectively. The same reduction pattern applies to the indirect CO_2, NO_x, and SO_2 emissions. Regarding the economic aspects, our analysis has indicated that such an investment in the residential sector is, in most cases, still not cost-efficient, because of the high installation cost. However, sensitivity analysis has demonstrated that green roofs become economically viable with only modest reductions (varying from 6% to 35%) in their installation cost, which are possible in the medium term because of technological progress or learning-by-doing due to their increased deployment. This prospect can be encouraging for local homeowners or real estate developers to eventually include green roofs in their preferable building's envelope upgrades.

Additionally, one should keep in mind that there are added associated environmental gains which are currently hard to quantify financially. In addition, following the results of our environmental simulations, the consideration of broadly applying green roofs at a wider urban scale can indeed upgrade the micro-climatic conditions of even spatially constrained urban areas, such as local neighborhoods. As a result, the resilience of urban communities against deterioration of climatic conditions can be enhanced – thus offering further environmental and economic advantages. Competent authorities should carefully consider this perspective in their efforts towards planning and applying green urban construction and renovation projects.

4 Systematic usage of green roofs in urban areas: Environmental and thermal investigation in different geometrical formations and climatic zones

Green infrastructure has been acknowledged as an efficient measure against environmental degradation that dominates in contemporary conurbations around the world. This chapter[6] presents an assessment of the environmental upgrade of built-up areas facilitated by the employment of green roofs. In order to achieve this, an attempt is made to incorporate main ecosystem services in an evaluation based on two different neighborhood typologies, considering two European cities with quite different climatic characteristics, namely Brussels (Belgium) and Limassol (Cyprus).

This chapter indicates that the systematic and expanded usage of green roofs in urban areas can add positively to the alleviation of thermal and air quality discomfort. Results show that the decrease in the air temperature of the urban canopy in Brussels, is generally higher and more widely spread than the one in Limassol. In addition, carbon dioxide sequestration potential is apparent at both geographical sites and in consistency with the air direction and the different height of buildings.

4.1 Introduction

Green infrastructure (GI) has been acknowledged as an efficient measure against environmental degradation that dominates in contemporary conurbations around the world (European Environment Agency, 2017b; United States Environmental Protection Agency, 2017). A solid definition of GI is: "*a strategically planned network of natural*

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[6] This chapter is part of a manuscript to be submitted for publication in the *Journal of Urban Climate*.

and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services." (European Commission, 2013). Several projects have been employed at a European level, with Hamburg, Malmo and Bratislava being some of the successful exemplars adopting versatile financing mechanisms in order to implement GI climate change adaptation measures (European Environment Agency, 2017a).

One of the main priorities set by the Urban Agenda for the EU (Pact of Amsterdam) are directly connected with sustainable land use and nature-based solutions. The Urban Agenda explicitly refers to upgrading buildings' energy efficiency, improving air quality in urban canyons, considering sprawl in urban planning and design, greening gray built environment, and reinvigorating brownfield areas (European Commission, 2016). An additional measure being considered is the increase of urban surfaces' water retentiveness against flooding events that are aggravated by climate change and cause increased infrastructure expenditure for local governments (European Environment Agency, 2016). It is worth noting that these priorities overlap with the Sustainable Development Goals set by the United Nations (United Nations, 2015), as well as the priority themes established in the New Urban Agenda adopted in Habitat III Conference (United Nations, 2017).

Adding to the previous priorities, Urban Innovative Actions, which is an EU's initiative acting as a resources platform for urbanized areas to implement innovative solutions, suggests that the efficient use of land and the containment of urban sprawl combined with systematic and purpose-oriented application of nature-based solutions comprise an inherent characteristic of a sustainable city model (European Regional Development Fund, 2018). Moreover, International Council for Local Environmental

Initiatives (ICLEI), which is a global network dedicated to promote sustainable urban solutions, urges regional, municipal and communal governments towards a systemic urban transformation, with nature-based development being an integral part of it (ICLEI Local Governments for Sustainability, 2018).

According to the recent report about urban adaptation to climate change by the European Environment Agency (2016), viable and sustainable future cities pioneer the integration of extended green areas into the built fabric intertwined with the confinement of urban sprawl. These areas can be realized by a systematic usage of green roofs in defined districts or neighborhoods. Green roofs act as a promising passive energy upgrade of the buildings' envelope and offer a variety of ecosystem services that can strongly improve the wellbeing of cities' inhabitants. Among the established ecosystem services provided by green roofs lie excess urban heat mitigation, storm-water run-off reduction, and carbon dioxide (CO_2) sequestration (Besir and Cuce, 2018; Shafique, Kim and Rafiq, 2018).

This chapter presents an assessment of the environmental upgrade of built-up areas facilitated by the employment of GI in accordance with the urban morphology characteristics of each area. In order to achieve this, a first attempt is made to comprehensively incorporate the aforementioned ecosystem services in an evaluation based on the examined morphological parameters of the neighborhood typologies, considering two European cities with quite different climatic characteristics, namely Brussels (Belgium) and Limassol (Cyprus). Regarding the examined regions, Limassol, the second largest city of the island, is the hottest in the region with heating degree days (HDD20/12) equal to 221 Kdays according to the METEONORM meteorological database (Meteotest AG, 2017)

Thus, the proposed evaluation is based on simulation results regarding both the urban thermal comfort enhancement and the CO_2 sequestration potential, as well as recent well-documented literature values that concern water retention capacity. This evaluation can help the formation of policy tools for assessing both the effectiveness and the applicability of such resilience promoting measures, since it provides helpful insights regarding basic ecosystem services of green roofs with respect to geometric and climatological characteristics of different urban formations, supplementarily to the observations and results in already existing literature. In addition, the study directly falls into one of European Union's fundamental policy challenges, namely addressing climate change in a scientifically robust way and consequently promoting solutions directed towards urban-scale application (European Commission, 2018).

4.2 Methodology

4.2.1 Case design

One of the main concerns regarding the transition from energy efficiency upgrade of individual buildings to city-level applied green infrastructure is the size and complexity of the examined area in order to evaluate the effects of the proposed sustainable solutions. An appropriate spatial study unit, from both a social and an engineering perspective, can be the neighborhood (Oke, 1988, 2006). Neighborhoods encompass the notion of community as "a group of people with an arrangement of responsibilities, activities and relationships,…under a defined geographical boundary" (International Organisation for Standardization, 2018) and their scale is equivalent to the one of a small or medium-sized supply and distribution energy system, thus being an acceptable design unit for urban planning procedures (Elci *et al.*, 2018).

Neighborhood scale is suitable for comprehending the interconnection between urban microclimatic alterations and urban architecture inside the urban canopy layer (UCL) (Battisti *et al.*, 2018). In this chapter, urban areas were designed from scratch representing either stand-alone neighborhoods or expansions of existing cities. Figure 27 depicts two selected urban forms, each of them solely comprised of either high-rise (4 floors) or low-rise (2 floors) building typologies, respectively. These two types of buildings are commonly found, mostly in residential neighborhoods of the selected locations, and can be representative examples for the needs of the current study. The ground formation represents the extreme case of having no exposed soil or any kind of vegetation. Only asphalt roads and dark concrete pavements are chosen in order to estimate the temperature differences at street level, between the initial designs and the green roof-integrated counterparts. The materials used for the ground formation have the same characteristics with the ones used in the actual urban figures.

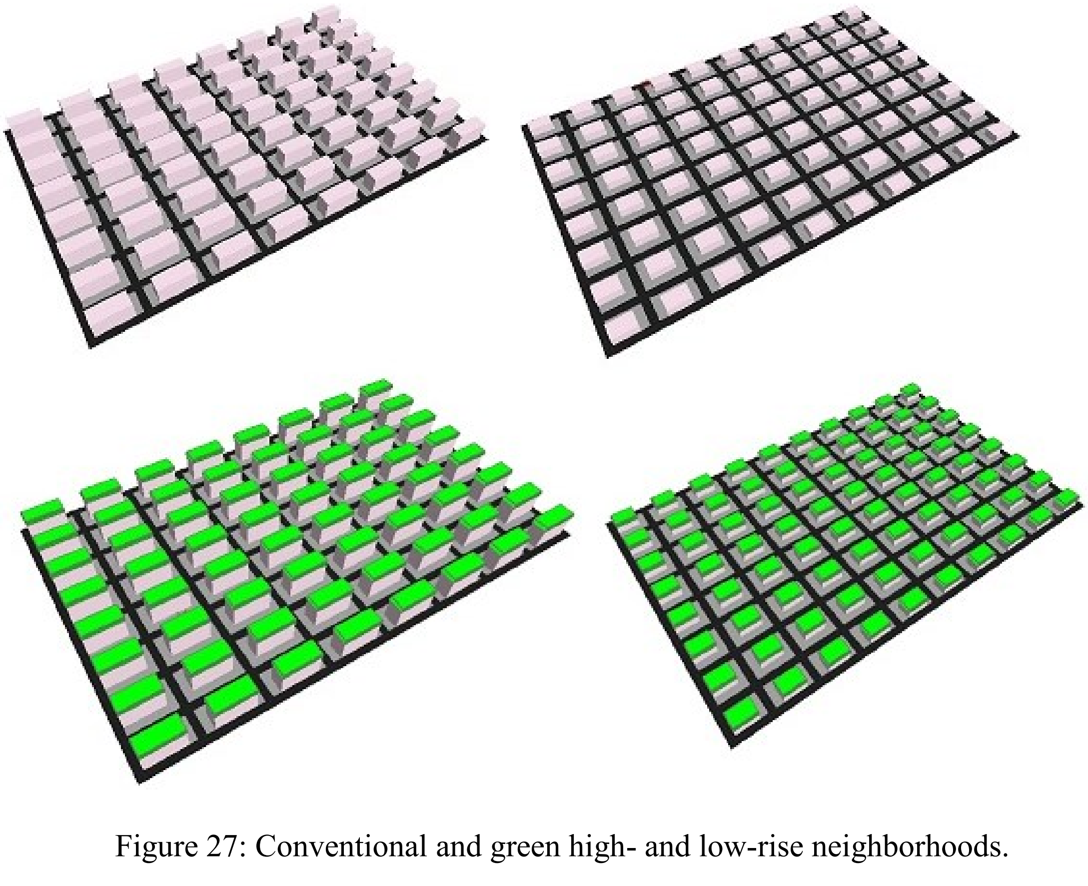

Figure 27: Conventional and green high- and low-rise neighborhoods.

4.2.2 Modelling parameters

The developed synergies of building surfaces with the neighboring environment comprise the fundamental element of microclimate models, which are broadly used by engineers and urban designers (Mirzaei, 2015). In this study, for the microclimatic investigation of the proposed neighborhoods, ENVI-met is used. It is a comprehensive microclimate simulation program, offering prognostic results through computational fluid dynamics analysis and incorporation of thermodynamics principles (ENVI_MET GmbH, 2018). The software facilitates the creation of three-dimensional models representing more confined urban areas, like neighborhoods, and allows for dedicated selection of vegetation types and various surface materials in order to dynamically examine the microclimatic interactions between buildings and the remaining urban environment (Koutra *et al.*, 2018).

The modelling platform of ENVI-met can be considered reliable, based on statistical correlations of measured and simulated values incorporated in recent studies, particularly when attention is given to comparisons between different scenarios and not the extraction of absolute values (Tsoka, Tsikaloudaki and Theodosiou, 2017). In fact, the coefficient of determination between the technically monitored and the simulated values of the average air temperature can reach 0.83 in a summer design day (Wang, Berardi and Akbari, 2016). However, certain limitations are also noticed in literature (Tsoka, Tsikaloudaki and Theodosiou, 2018). Some of these are the comprehensive calculation of radiation fluxes, the creation method of the grid system, the assumption of static wind and cloud conditions throughout the simulation time, and the lack of the option of full-forcing wind velocity and direction.

Correct parameterization of ENVI-met (especially in terms of acceptable duration of simulation and accurate initial conditions) is crucial for the simulation results to be as reliable as possible and to reflect the real environmental conditions (Salata *et al.*, 2016; Roth and Lim, 2017). In addition, special attention should be attributed to the choice of the following modelled space design parameters: a) height of selected buildings, b) height to width (H/W) (aspect) ratio of street canyons, and c) the horizontal and vertical dimensions of the grid cells, due to their contribution to the determination of air temperature and mean radiant temperature values (Qaid *et al.*, 2016; Tsoka, Tsikaloudaki and Theodosiou, 2018).

The spatial allocation of three basic components of urban design, i.e. urban greening, buildings and paved surfaces plays a significant role in local temperature fluctuations and thereby thermal discomfort conditions (Gago *et al.*, 2013). This is mainly due to their direct effect on the air velocity patterns inside urban canyons and the absorption or reflectance of solar radiation (Lobaccaro and Acero, 2015; Chatzidimitriou and Yannas, 2016). The aforementioned parameters are taken into consideration in this analysis. Tables 7 and 8 contain the microclimatic parameters used in the ENVI-met configuration files for the two selected cities and the design characteristics of the selected neighborhoods, respectively.

Table 7: Microclimatic parameters for Brussels and Limassol

Parameter	Value	
Simulation day	Hottest summer day for the selected locations	
Start simulation time	06:00 (In order for the simulation to be in accordance with the atmospheric procedures)	
Nesting grids around main area	3 (In order to avoid boundary effects)	
Meteorological inputs	Dry bulb air temperature (T_a) and relative humidity (RH) (Simple forcing was used)	
Total simulation hours	32 h (Minimum required duration is 6 h in order to prevent undesired effects (possibly caused by the transitory conditions in the initialization phase of the simulation, (ENVI_MET GmbH, 2017a))	
Roughness Length z0 at Reference Point	0.01 (Urban environment)	
	Brussels	Limassol
Wind speed in 10m above ground	4.15 m/s (Average value)	1.32 m/s (Average value)
Wind direction (N=0)	164.17 deg	189.89 deg
Adjustment factor for shortwave solar radiation	1.00	0.82
Min hourly T_a / Max hourly T_a	17.90 °C / 31.60 °C	26.40 °C / 36.00 °C
Min hourly RH / Max hourly RH	42.00 % / 82.00 %	50.00 % / 85.00 %

Table 8: Urban design characteristics for Brussels and Limassol.

Parameter	Value	
Modelled area orientation	North	
Grid size	5.00 m × 5.00 m × 3.00 m	
Buildings' height	Low-rise	High-rise
Modelled area size (in grids)	59(x) × 39(y) × 4(z)	63(x) × 39(y) × 10(z)
Density (built area/total area)	20.86%	26.05%
Aspect ratio	0.40	0.80

4.2.3 Environment-related parameters

For the green roof systems, the plant Sedum Sediforme has been used for all green scenarios. This succulent plant can withstand extreme draught conditions and doesn't require any special watering treatment, while it can also withstand colder climatic conditions (Nektarios *et al.*, 2014). Table 9 contains basic parameters of the specific plantation that were taken under consideration for the microclimatic simulations.

Table 9: Simulation parameters for sedum sediforme

Parameter	Value	Unit
Height of plants	0.25	m
Albedo	0.22	-
Transmittance	0.30	-
Root Zone Depth	0.15	m
CO_2 Fixation Type	C4	-
Water retention capacity (average)	60.3 (Limassol)	%
	70.9 (Brussels)	%

For the CO_2 sequestration potential of the selected green roof system, the fixed values incorporated in the simulation software were used. For the water retention capacity of the green roof, the values used for the overall evaluation are based on the results provided by M. Akther et al. (Akther *et al.*, 2018) and K. Soulis et al. (Soulis, Ntoulas, *et al.*, 2017), for the case of Brussels and Limassol, respectively.

4.3 Results and discussion

4.3.1 Microclimatic results

Figure 28 presents the air and mean radiant temperature fluctuations of a center grid cell of the conventional modelled low- and high-rise neighborhoods, at a height of 1.50 m above ground, for Brussels. For the sake of brevity, the related figures for Limassol are omitted but are available upon request. These graphs allow us to find the hottest hour of the simulation period, which can be used as an indicative time reference for the subsequent calculation of air temperature decrease.

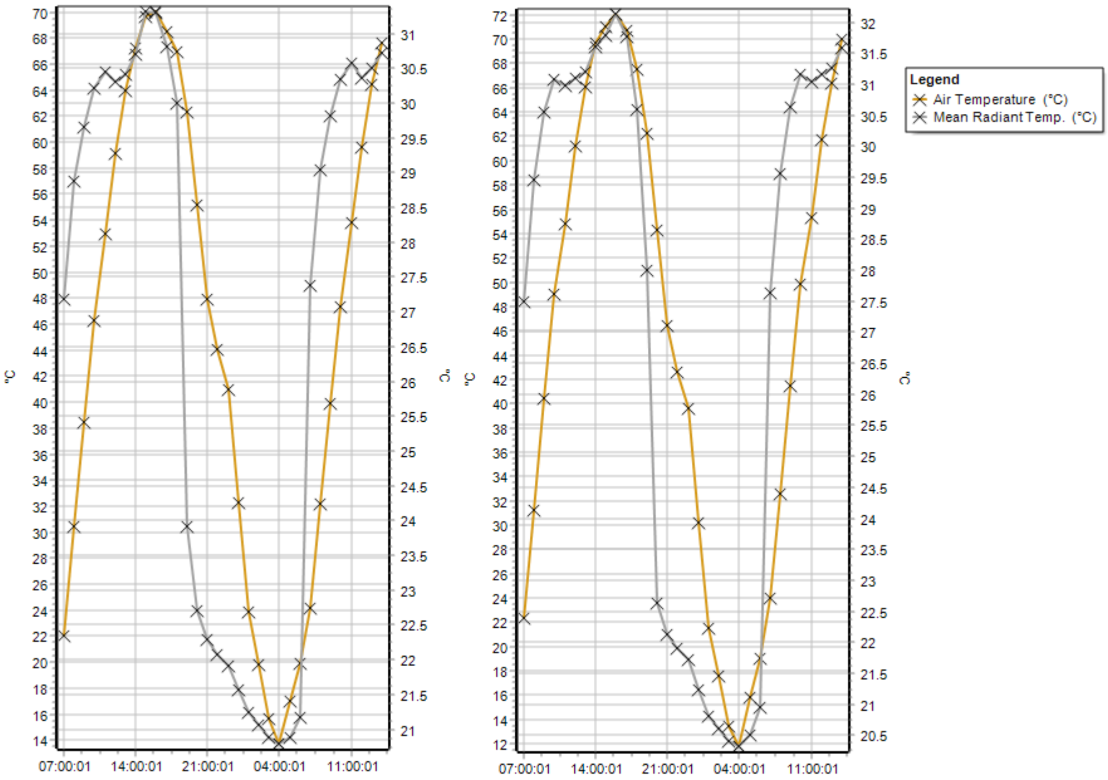

Figure 28: Air Temperature (Ta) and Mean Radiant Temperature (MRT) fluctuation for the whole simulation period for high- (first chart) and low-rise (second chart) grey neighborhoods in Brussels.

In addition, Figures 29-32 indicatively presents the absolute air temperature differences between the conventional and proposed green roof scenarios for the low and high-rise neighborhood in Brussels and Limassol, at a pedestrian level (1.50 m).

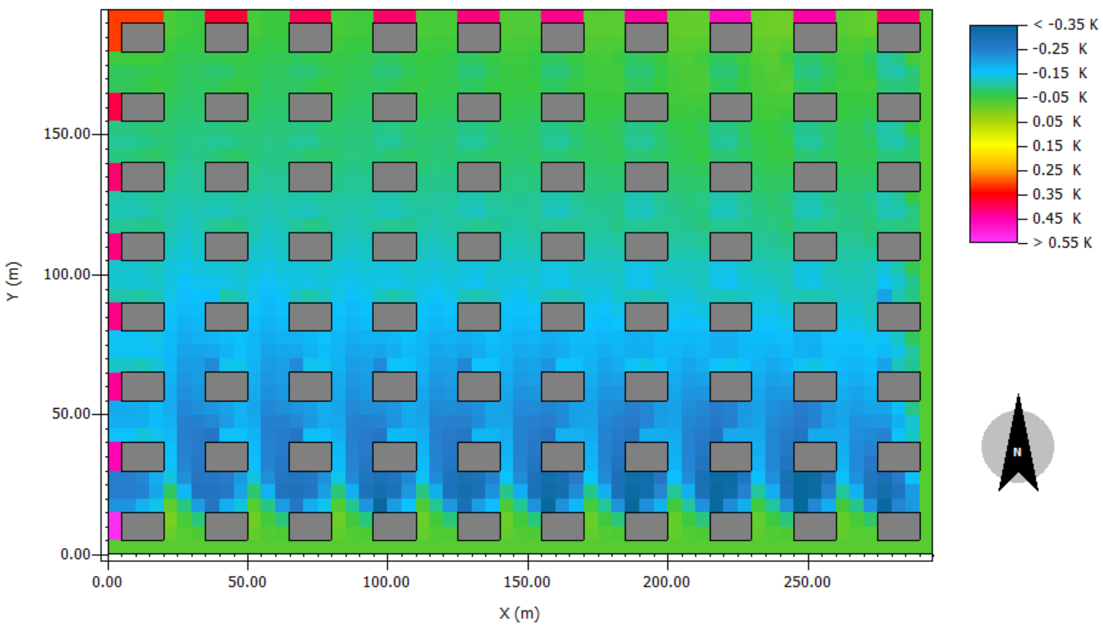

Figure 29: Absolute air temperature differences at 15:00 pm between gray and green low-rise neighborhood in Brussels.

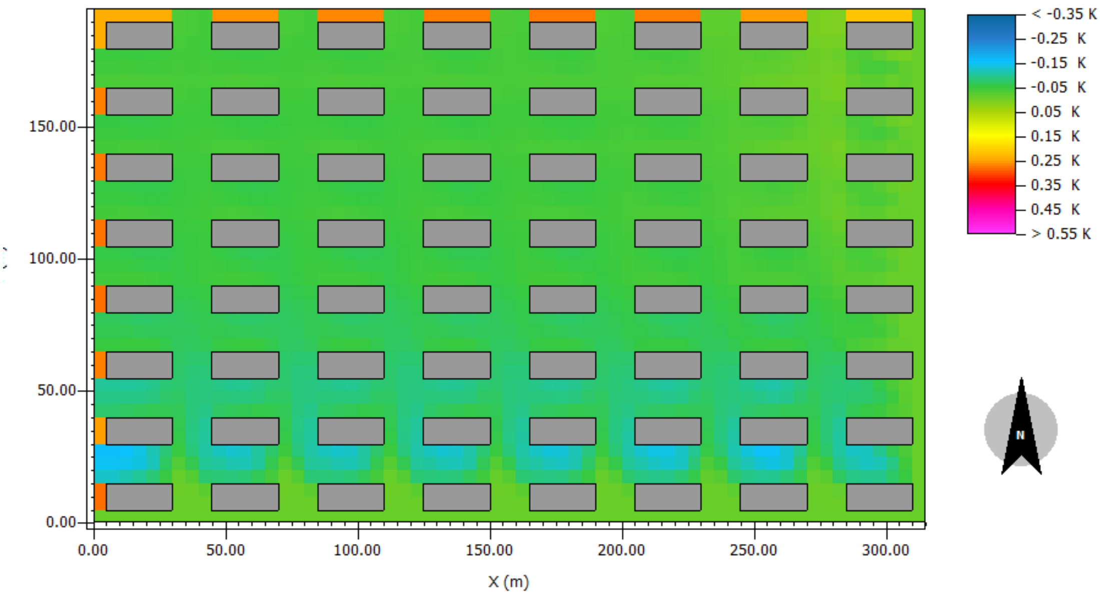

Figure 30: Absolute air temperature differences at 15:00 pm between gray and green high-rise neighborhood in Brussels.

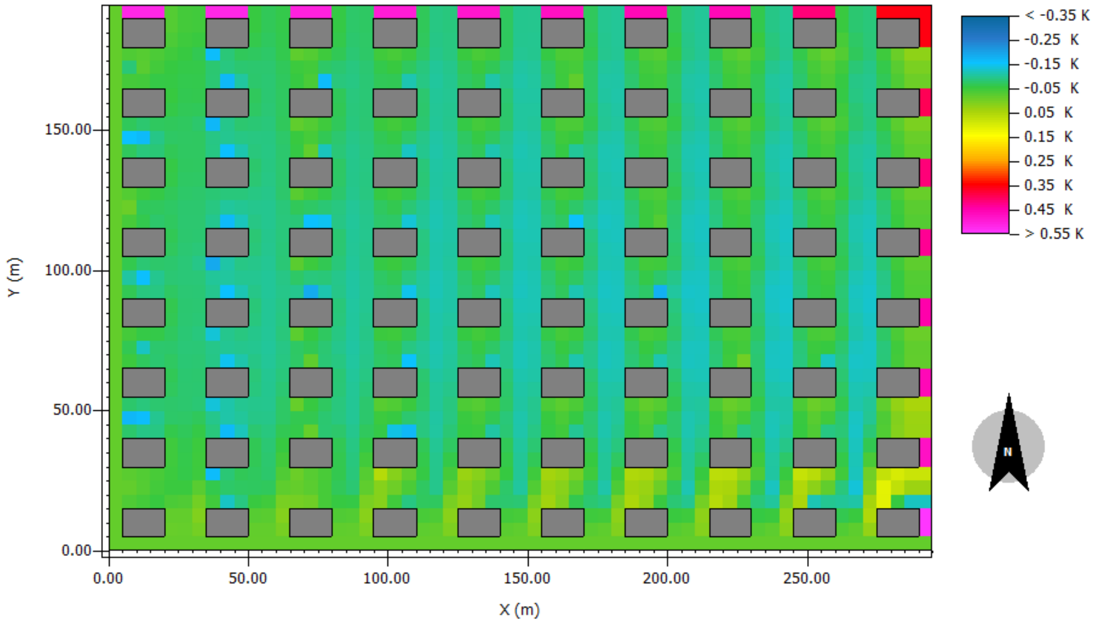

Figure 31: Absolute air temperature differences at 14:00 pm between gray and green low-rise neighborhood in Limassol.

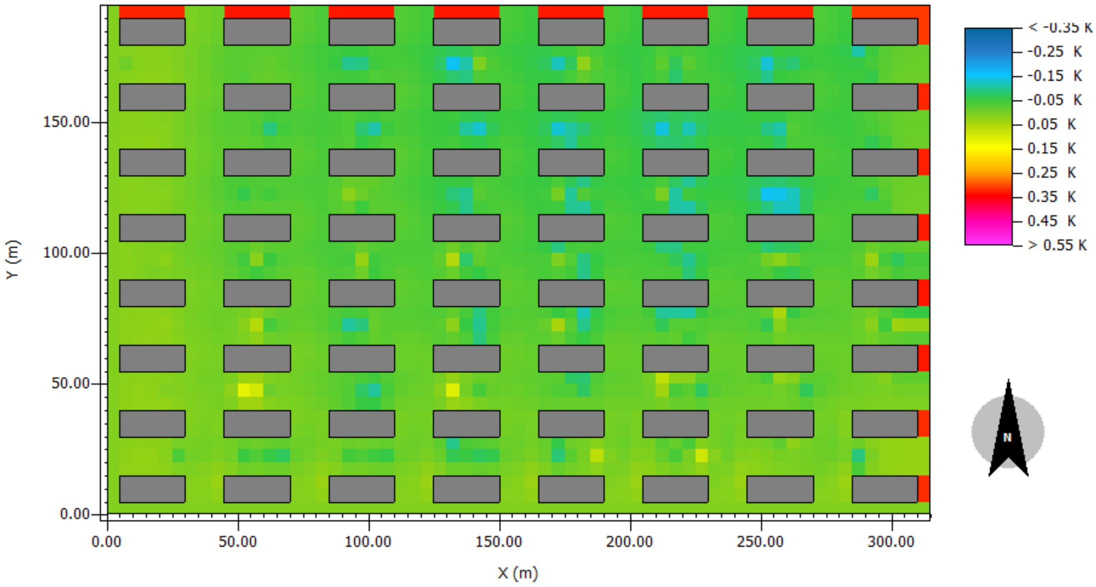

Figure 32: Absolute air temperature differences at 14:00 pm between gray and green high-rise neighborhood in Limassol.

The daytime effect on the maximum decrease of absolute air temperature at pedestrian level due to the systematic deployment of green roofs at an urban neighborhood located either in Brussels of Oceanic climate (Cfb) or in Limassol of Subtropical-Mediterranean climate (Csa) vary between 0.15 and 0.35 °C. The decrease in the air temperature of the urban canopy in Brussels, is generally higher and more widely spread than the one in Limassol, mainly due to the fact that the wind speed in the former location is more than 3 times higher. The numeric findings are consistent with that of Susca (2019), in whose review study, a decrease not exceeding 0.5 °C is observed.

4.3.2 Environmental evaluation

Figures 33-36 represent the absolute reduction of CO_2 concentration in mg m^{-3} at pedestrian level (i.e., 1.50 m).

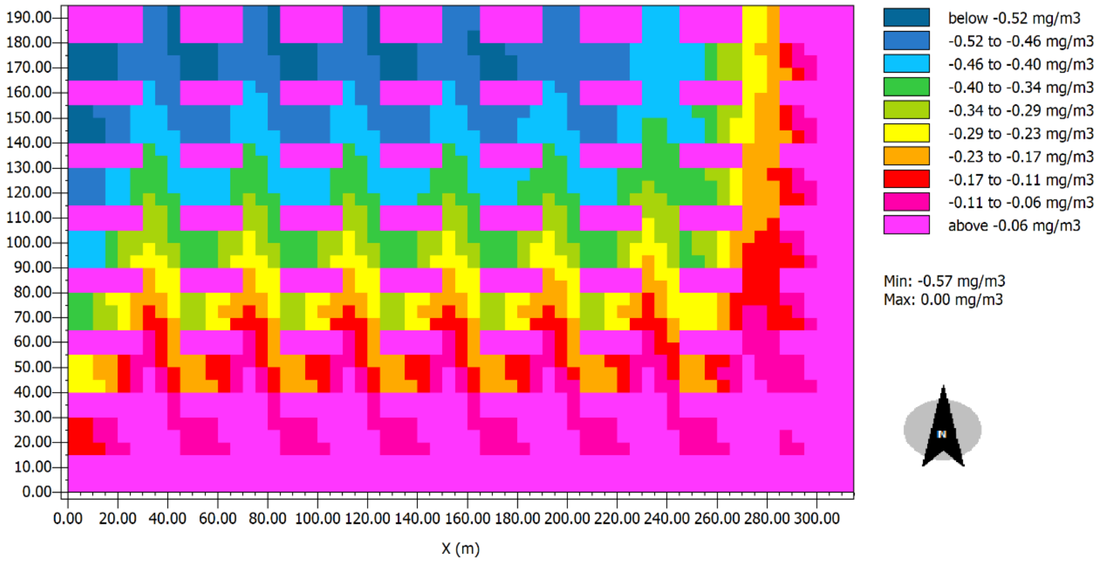

Figure 33: Absolute CO_2 concentration differences at 15:00 pm between gray and green high-rise neighborhood in Brussels.

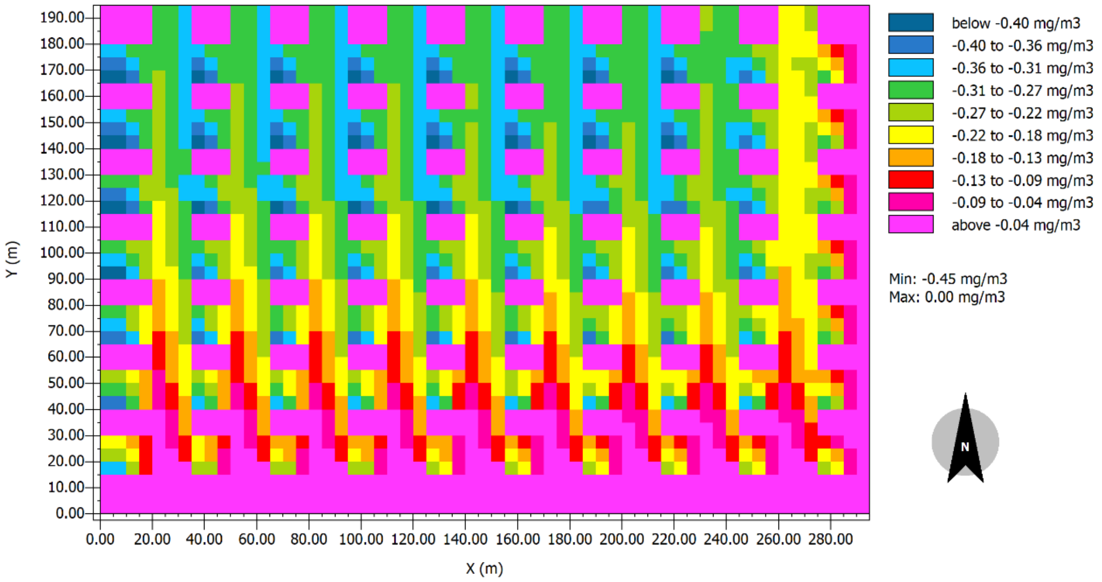

Figure 34: Absolute CO_2 concentration differences at 15:00 pm between gray and green low-rise neighborhood in Brussels.

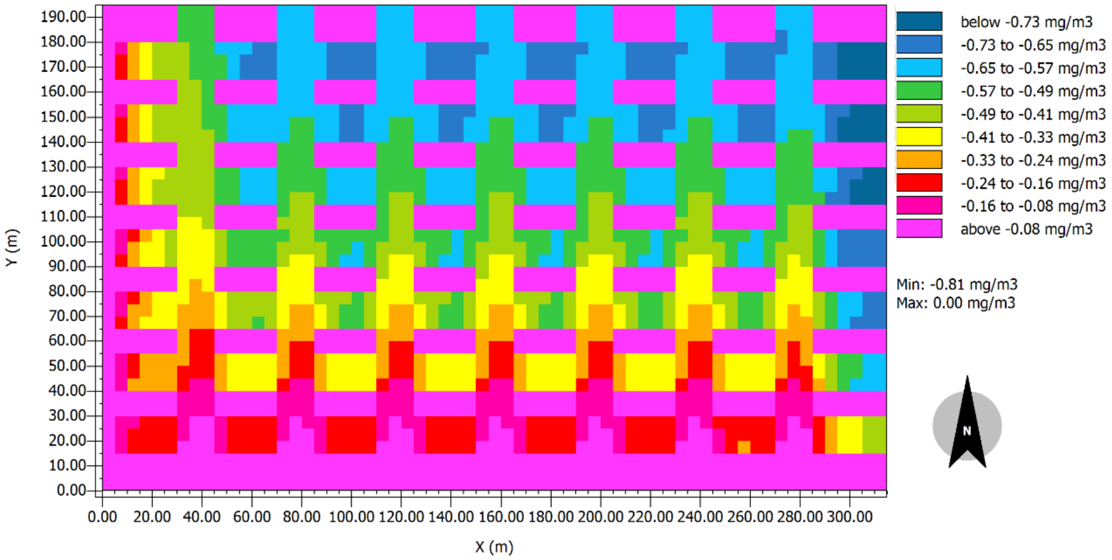

Figure 35: Absolute CO_2 concentration differences at 14:00 pm between gray and green high-rise neighborhood in Limassol.

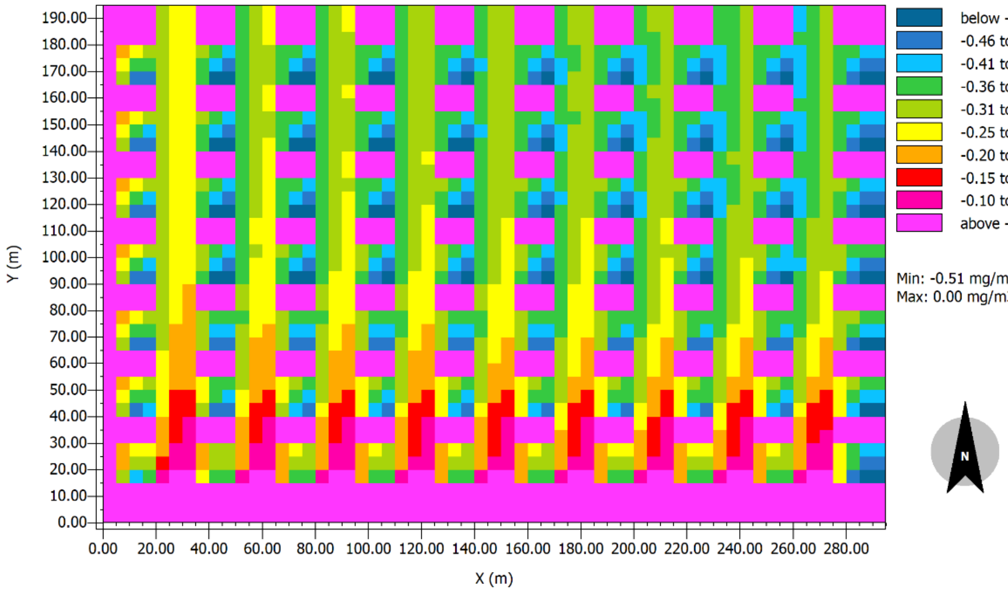

Figure 36: Absolute CO_2 concentration differences at 14:00 pm between gray and green low-rise neighborhood in Limassol.

As can be seen from the above figures, the application of green roofs in the case of Limassol yields more positive results, since the absolute difference in CO_2 concentration at the pedestrian level is 0.21 mg m-3 higher than the one noticed in Brussels. In general, the CO2 sequestration potential is apparent at both geographical sites and in consistency with the air direction and the different height of buildings.

Maximum CO_2 concentration differences for each scenario along with the retention capacity values obtained from literature review are summarized in Figure 37 below. Someone can note the positive effect of the succulent Sedum Sediforme’s ecosystem services, both in Brussels of the oceanic climate and in Limassol with the warm temperate climatic characteristics. Water retention capacity is more apparent in the case of Brussels, with the respective values being around 16.70 % higher. On the contrary, reduction in CO_2 concentration at pedestrian level for the case of Limassol, is 40.38% and 15.00% higher for high-rise and low-rise neighborhoods, respectively.

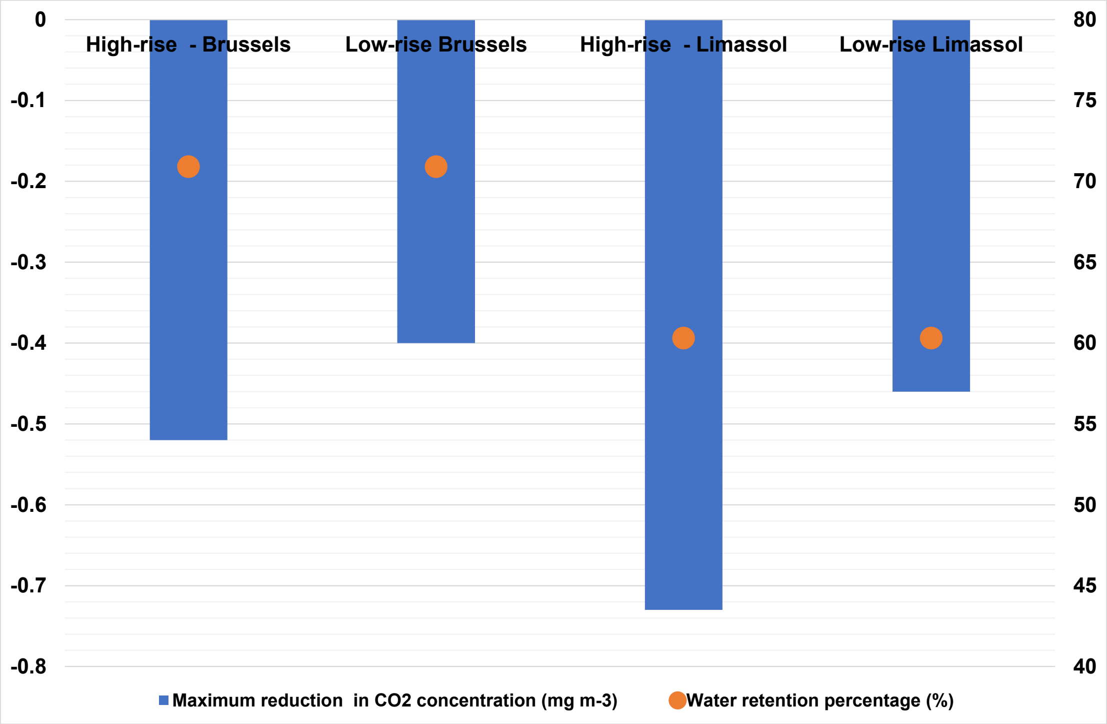

Figure 37: Maximum absolute differences in CO2 concentration and water retention percentages.

4.4 Conclusions

Current research is on its way of espousing integrated methods of urban-scale modelling, environmental smart sensing applications and mitigation measures, and thus being able to underpin effective solutions against imminent climate stress incidents inside cities (Nyuk Hien, 2016). In order to overcome any impediments caused by possible reluctance of administrative authorities to implement GI projects in their local communities, the following steps should be followed: a) numerical description of the excess urban heat, b) determination of a tolerable level of heat stress, and c) specification of the size and quantity of the proposed measures (Kleerekoper, Van Esch and Salcedo, 2012).

For a big number of large cities around the world, Estrada, Botzen, & Tol (Estrada, Botzen and Tol, 2017) claim that global and local climate change jointly create negative economic effects and if local initiatives on attenuating urban thermal stress are neglected, mitigation efforts on global climate change can lose great part of their effectiveness towards curtailing severe climate impacts. According to their recent study, the percentages of lost Gross Domestic Product (GDP) for the median city of those examined are 1.4% and 1.7% in 2050 for the RCP 4.5 and RCP 8.5[7], compared to 0.7% and 0.9% loss, respectively, due to global climate change alone.

In this direction, Peng & Jim (Peng and Jim, 2015) suggest that a wider application of policies promoting green roof installations in modern and densely populated cities, like Hong Kong, can help towards combating climate change, with the entire yearly monetary value of district-scale implementation of extensive green roofs being USD 12.98 million with unit value of USD 10.77 m^{-2} $year^{-1}$. Even when local environment is of primary interest, this nature-based solution can still be effective, although the accompanying high installation and maintenance costs may be deterring factors for building owners to invest (Sproul *et al.*, 2014).

As shown in this chapter, the systematic and expanded usage of green roofs in urban areas can add positively to the deterioration of thermal and air quality discomfort, while keeping in mind limitations regarding both the simulation parameters used and the

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[7] According to the Representative Concentration Pathway (RCP) adopted by the IPCC for its 5th Assessment Report (AR5) in 2014, global annual GHG emissions (measured in CO_2-equivalents) reach maximum in 2040 and decrease afterwards in RCP 4.5, while in RCP 8.5, emissions keep increasing throughout the 21st century (Prather *et al.*, 2013)

relatively confined number of selected scenarios of this specific study. Results indicate that the decrease in the air temperature of the urban canopy in Brussels, is generally higher and more widely spread than the one in Limassol. In addition, CO_2 sequestration potential is apparent at both geographical sites and in consistency with the air direction and the different height of buildings. Through systematic implementation of green roofs along with other types of nature-based solutions, excessive urban energy consumption, flooding incidents inside cities, extreme air temperatures and production of greenhouse gases can be naturally rectified (Nesshöver *et al.*, 2017).

5 Summary of findings and recommendations for future work

In the context of sustainable cities, the eco-city can be a successful type of contemporary urban formation, where ecological design, passive solar technologies and urban green prevail. A part of the eco-city concept can be realized by green roof technology, a nature-based solution which compensates for the greenfield sites possibly occupied by new buildings, in the cases of city planning extensions or construction of new settlements and is a main element of passive design in highly efficient buildings (nZEBs, ZEBs, etc.) that are integral parts of sustainable cities.

This doctoral research has investigated this technological option for improving the sustainability in urban areas, with a preliminary focus on buildings. The appropriateness of this nature-based solution has been assessed with the aid of energy, environmental and economic modelling. With the aid of the selected simulation software, and going from individual building to neighborhood scale design and modelling, useful insights have been extracted. This work is one of the few studies to comprehensively examine the energy savings of such nature-based solutions in the Mediterranean area. Moreover, sensitivity analysis for the economic viability of green roofs as well as exploration of urban microclimatic conditions' advancement due to expanded urban usage have been jointly examined, and the results of the research have already been included in two publications in peer-reviewed journals.

For the tertiary sector of Cyprus, which is presented in Chapter 2 of this dissertation, primary energy savings for heating in the case of an uninsulated office building range between 6% and 13%, and these values almost double in perimetrically insulated buildings. Similar results, with some differences between the two green roof options, occur for the cooling operation of the buildings. These savings lead to corresponding reductions in CO_2, NO_x and SO_2 emissions. The economic analysis has shown that the green roof technology is still not cost-effective to be implemented in the selected type of office building, despite the direct monetary energy benefits and the decreased social environmental costs. High initial installation cost due to the complexity of the necessary structure and the subsequence maintenance expenses sets an impediment for private investors.

In Chapter 3, which focuses on the residential sector of Cyprus, some key findings for the operation of green roofs are as follows. Primary energy savings on heating mode can reach 30% for both building typologies, while under summer operation 35% and 25% reductions in primary energy consumption are found, for the considered single-family and multi-family buildings, respectively. The same reduction pattern applies to the indirect CO_2, NO_x, and SO_2 emissions. Regarding the economic aspects, the analysis has indicated that such an investment in the residential sector is, in most cases, still not cost-efficient, because of the high installation cost.

Although the initial economic results make green roofs unattractive for private investors, sensitivity analysis has demonstrated that green roofs become economically viable with only modest reductions (varying from 6% to 35%) in their installation cost, which are possible in the medium term because of technological progress or learning-by-doing due to their increased deployment. It is also possible for local authorities to provide direct monetary incentives to landowners such as subsidies and grants or indirect financial motivations like tax exemptions and increased structuring coefficients, thus immediately promoting the wide application of this urban sustainable solution. In societies with high economic and educational level, like in the case of Cyprus, real estate market could flourish, since prospective buyers looking for sustainable buildings of high energy performance would be attracted.

In addition, following the results of the environmental simulations, the consideration of broadly applying green roofs at a wider urban scale can indeed upgrade the micro-climatic conditions of even spatially constrained urban areas, such as local neighborhoods. As a result, the resilience of urban communities against deterioration of climatic conditions can be enhanced – thus offering further environmental and economic advantages. In this direction, certain standards and regulations could be implemented for boosting green roof constructions. For instance, in Linz, Austria, it is obligatory for new buildings with a roof area occupying more than 100 m^2 to be covered with a green roof. Moreover, in Copenhagen, Denmark, all municipal buildings must be covered with a green roof, as provide by Danish Green Roof Policy (Jovanovic *et al*., 2020).

For the case of comparing two alternative and very different climatic zones, presented in chapter 4, the study indicates that the systematic and expanded usage of green roofs in urban areas can add positively to the alleviation of thermal and air quality discomfort, while keeping in mind limitations regarding both the simulation parameters used and the relatively confined number of selected scenarios of this specific study. Results indicate that the decrease in the air temperature of the urban canopy in Brussels, is generally higher and more widely spread than the one in Limassol, without, however, being prominently different. In addition, CO_2 sequestration potential is apparent at both geographical sites and in consistency with the air direction and the different height of buildings. Therefore, urban neighborhoods at both locations can be benefitted from the adoption of such nature-based retrofit projects.

The results of this research indicate that the systematic application of green roofs as a passive energy upgrade measure, provides significant benefits not only for the individual buildings but also for the whole urban area. These benefits vary from energy savings and reduction of direct and indirect pollutant emissions to urban thermal and air quality improvement. One should keep in mind that due to the wide extent of the specific scientific area explored, certain limitations have been imposed. However, such drawbacks can be addressed in future work.

Thus, in terms of context, the research presented in this dissertation can be expanded in larger and more complex urban areas, while more ecosystem services, such as ecosystem maintenance, aesthetic added value, pollution mitigation, and flood protection can be explored. Other forms of green and blue infrastructure, like green walls and water-ponds, can also be incorporated in the analysis. In terms of methodology, for a more sophisticated investigation of the contribution of different microclimatic, energy, environment, economic and morphological scenarios, data analysis techniques can also be deployed. The new and more comprehensive results could ultimately lead to the development and use of life cycle sustainability assessments of urban areas in an ISO-like compliant way with a focus to neighborhood or even larger district scale.

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APPENDIX I

Supplementary figures illustrating the sensitivity analysis results appearing in Section 3.4.3.2

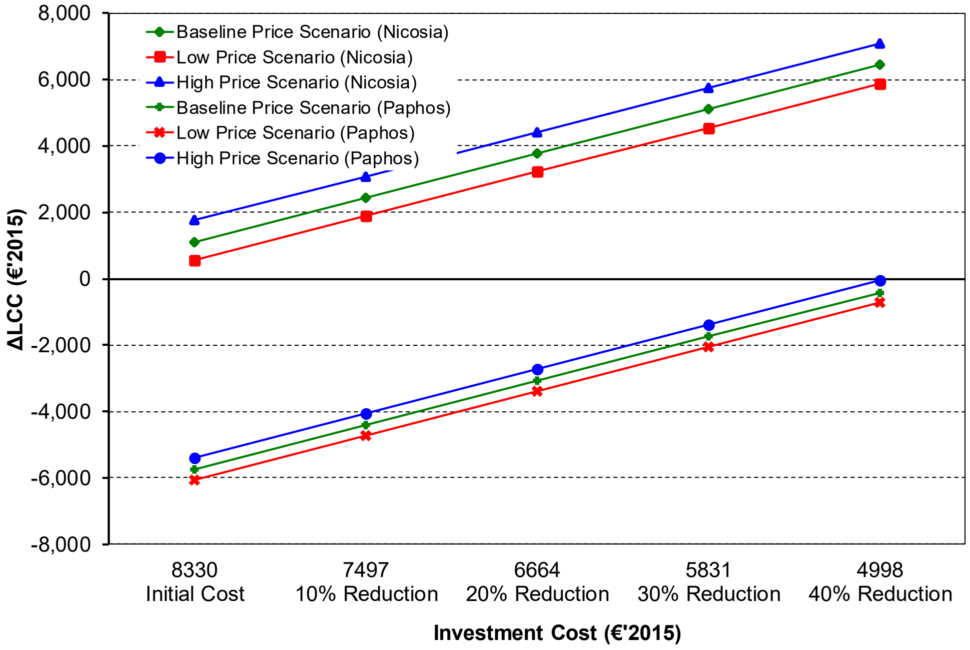

Figure 38: Sensitivity analysis of the first green roof system (Helichrysum Orientale) for the uninsulated single-family building in Nicosia and Paphos.

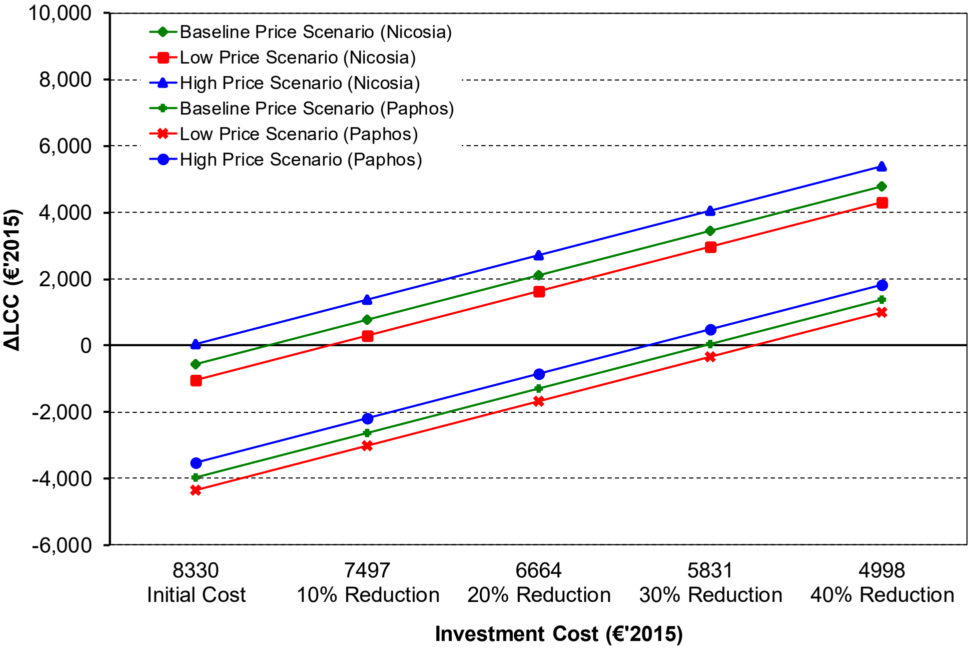

Figure 39: Sensitivity analysis of the first green roof system (Helichrysum Orientale) for the insulated single-family building in Nicosia and Paphos.

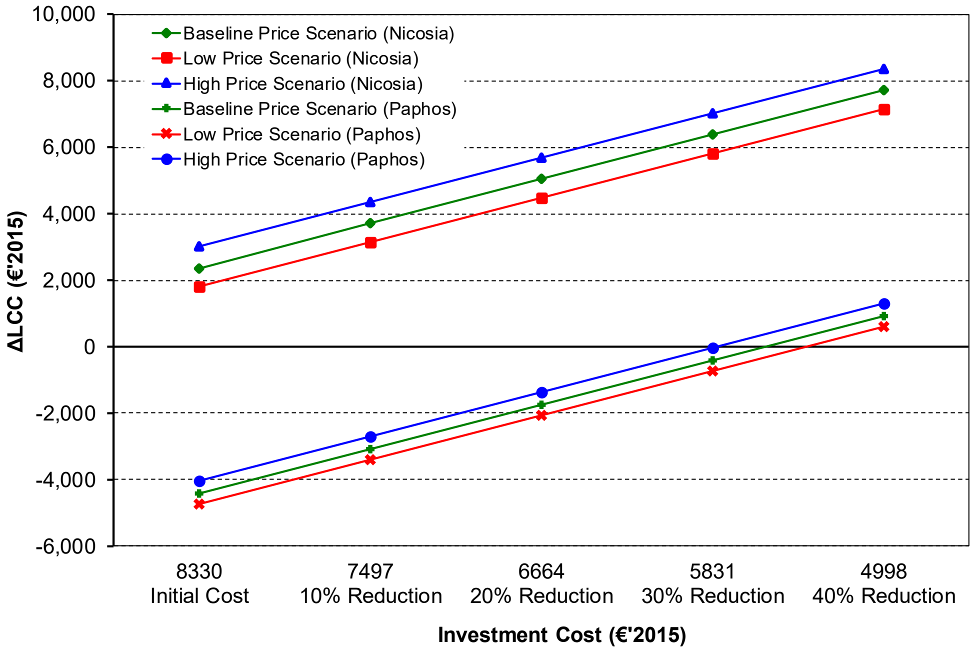

Figure 40: Sensitivity analysis of the second green roof system (Sedum Sediforme) for the uninsulated single-family building in Nicosia and Paphos.

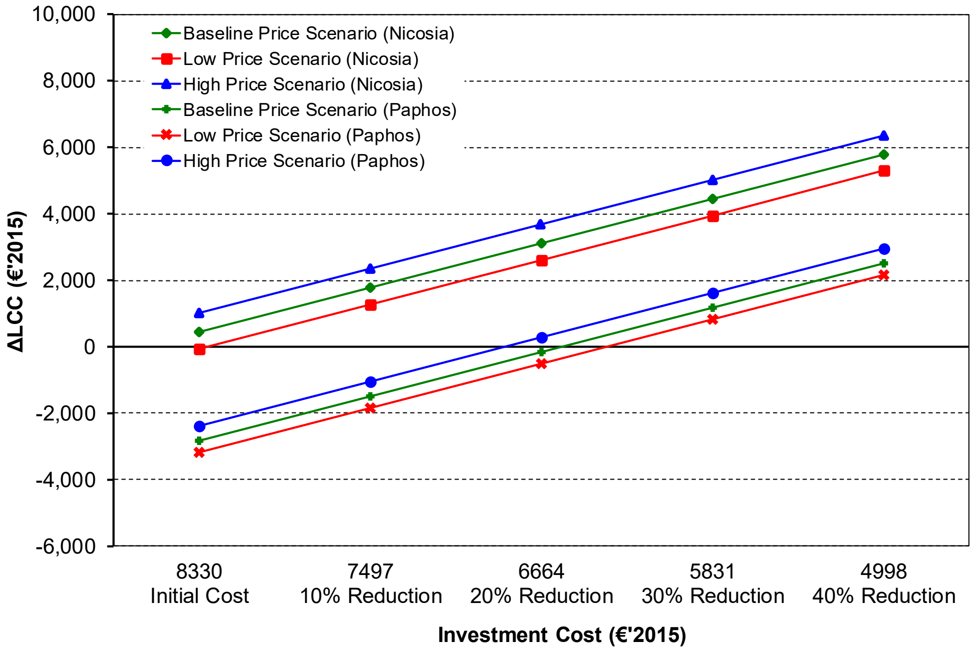

Figure 41: Sensitivity analysis of the second green roof system (Sedum Sediforme) for the insulated single-family building in Nicosia and Paphos.

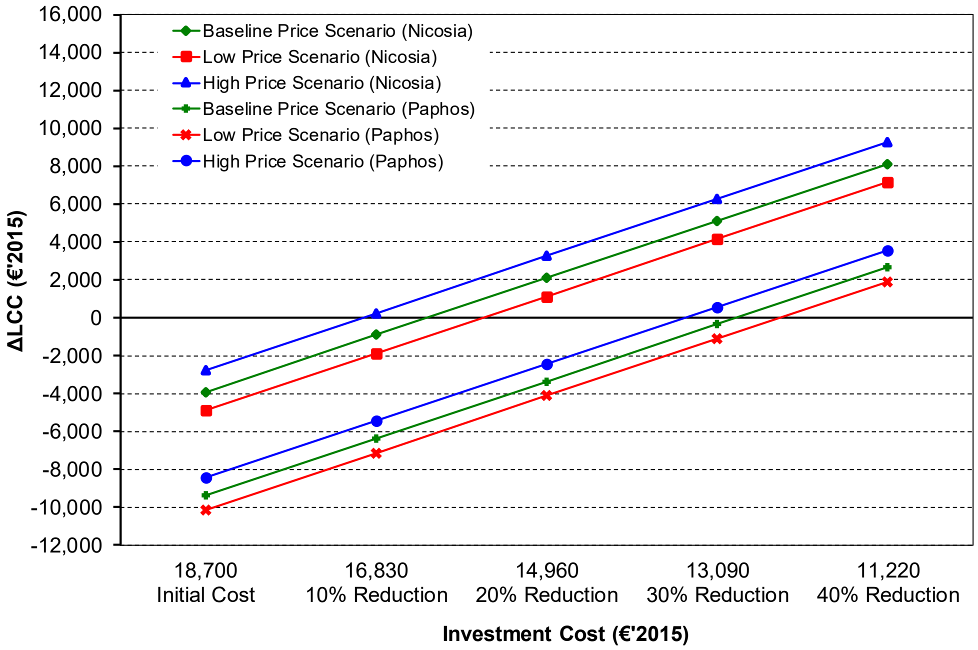

Figure 42: Sensitivity analysis of the first green roof system (Helichrysum Orientale) for the uninsulated multi-family building in Nicosia and Paphos.

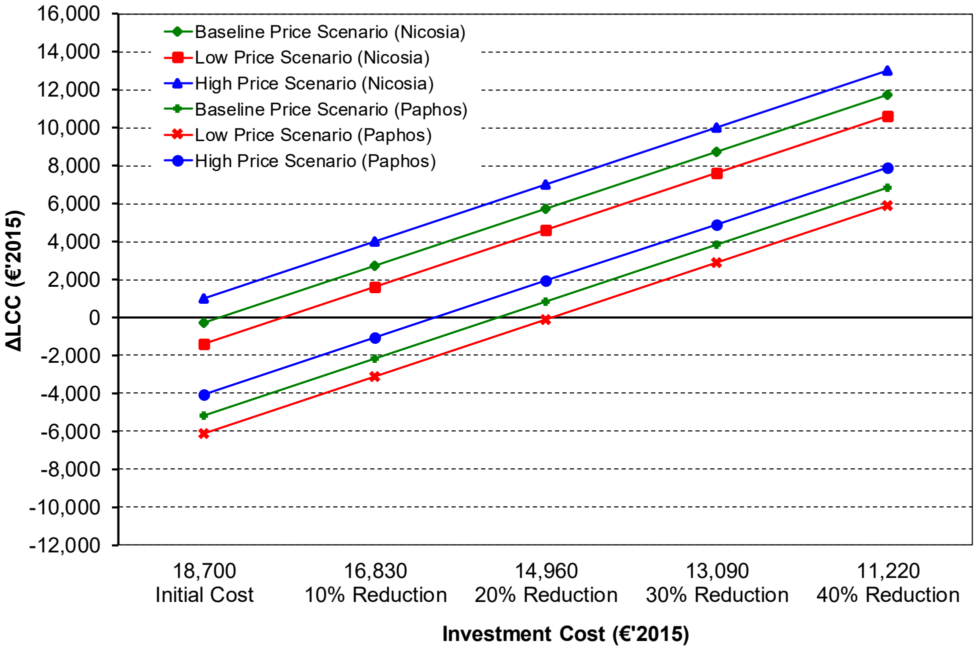

Figure 43: Sensitivity analysis of the first green roof system (Helichrysum Orientale) for the insulated multi-family building in Nicosia and Paphos.

APPENDIX II

Supplementary data files used for the analysis presented in Chapters 2-4.

- Excel spreadsheets with energy, environmental, and economic calculations.
- Envi-Met simulation data files.
- AutoCAD drawings of selected building typologies.
- Weather- and vegetation-related data files.

The above-mentioned files are available in the following link:

Doctoral Dissertation - Ziogou - Supplementary Data