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THE ENERGY CONSERVATION PROVIDED BY GREEN ROOFS ON METAL SHEETS IN A TROPICAL CLIMATE

Bachelor Thesis | Jitta Meijer

Colophon

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Educational institution:	University of Twente Faculty of Engineering Technology Course Civil Engineering Postbus 217 7500 AE ENSCHEDE www.cit.utwente.nl
Sponsor:	Bioclimatic commercial centre 'Techos Verdes' San Pedro Sula, Honduras
Author:	Jitta Meijer j.c.meijer@student.utwente.nl
Supervisors:	University of Twente Ir. A.G. Entrop a.g.entrop@ctw.utwente.nl Ing. G.H. Snellink g.h.snellink@ctw.utwente.nl Bioclimatic commercial centre 'Techos Verdes' Arch. A. Stassano adobe.y.viento@sigmanet.hn
Place:	Enschede
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University of Twente
Enschede - The Netherlands

Techos Verdes
Sistemas-Jardin para Techos y Paredes

Preface

In this report I present the results of research done for the bachelor thesis of my study civil engineering at the University of Twente. During this research I have lived for 4 months in a tropical climate and experienced all the (dis)advantages of this climate.

The main subject of my research is the performance of green roofs in a tropical climate. Green building technologies have always been of special interest for me. My attention was drawn by green roofs because of their multifunctional solution to multiple urbanization problems. With this research I hope to contribute to the popularity and knowledge discrimination of green roofs in tropical areas.

The empirical research has been done at and sponsored by the bioclimatic commercial centre "Techos Verdes", San Pedro Sula – Honduras. During the research period, September 2008 – January 2009, I have worked with Arch. Angela Stassano. I would like to thank her for the freedom she gave me to design and do the research in my style and to do it my way, as well as providing the facilities to perform it.

The counterpart for my research is the faculty of Engineering Technology at the University of Twente. First of all, I would like to thank my supervisors ir. A.G. Entrop and ing. G.H. Snellink. I appreciate the attentive readings of my manuscripts, the useful critics and their subtle hints when problems occurred. Second I would like to thank J.E. Avendano Castillo Msc. for the generous help during the pre-work of my thesis and in the search for a sponsor.

Last but not least, I want to thank my parents for their encouragements and support in many ways. Without them I wouldn't be where I am now.

Jitta Meijer
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Abstract

Green roofs are an ancient building technique and were already constructed in the days of Mesopotamia. In the last few decades they have made a re-appearance in the building sector. Green roofs have an ecological character and are especially useful in urban areas where they can oppose the effects of the current urbanization problems.

Most of the current worldwide green roof performance research is based on a more or less specific design for concrete slabs in moderate climates. This research distincts itself in two ways; the research is performed in a tropical climate, and their performance was studied on metal sheet roofs, the most commonly used roofing material in the area of San Pedro Sula, Honduras.

The climate has a substantial influence on the circumstances the research is in. Also, the climates influence on the building techniques used in Honduras is substantial. Insulation is far less important than in a moderate climate. Instead of preventing heat entering by insulation, natural ventilation techniques are often used to let excess heat flow out of a building. Another difference due to the climate is the plant selection. The tropical climate asks for another type of vegetation, than the most used type; sedums. The search for the ideal plant is not yet completed, criteria include; growth control, heat-, drought, - and rain resistance.

The use of corrugated iron sheets influences the characteristics of the roof. Compared to concrete slabs, corrugated iron sheets have a lower, almost negligible R-value. This results in fast transportation of incoming as well as outgoing heat. A corrugated iron sheet is a better radiant barrier, which means it reflects a higher rate of incoming (solar) radiation than concrete.

The advantages of green roofs are undoubtedly numerous from the ecological part of view and are especially suitable for areas with a high building density. In these areas more and more natural surfaces are covered by building materials such as concrete, metal and asphalt. This transduction of used materials influences the environment. Problems with impervious surfaces include higher ambient air temperatures. Green roofs are one potential remedy for this problem.

Green roofs act positively on the inner climate of a building and prevent heat radiation to the surrounding area as well. The green roofs cool a building by providing shadow over the roof, a main factor in passive cooling. The plants use a substantial part of the solar radiation for their biological functions, in so doing working as a radiant barrier. Furthermore they increase the insulation value and heat capacity of a roof. All these factors reduce the heat gain of a building and can save energy consumption for air conditioning, which affects the ambient air temperatures.

Establishing plant material on rooftops provides a multifunctional solution for the urban problems of the 21st century. Environmentally speaking there are no known disadvantages. Next to energy conservation and lowering ambient air temperatures benefits include storm water management, mitigation of the urban heat island effect, increased longevity of roofing membranes, and mitigation of noise and air pollution, as well as a more aesthetically pleasing environment in which to work and live.

The practical part of this study uses experimental data collected from two scale models, placed in Honduras (San Pedro Sula), a hot humid climate zone. Measurements were taken of the indoor air temperature as well as the metal sheet temperature, to determine differences among a normal and a green roof in their energy performances.

The data collected from the scale models was analyzed to qualitatively study the characteristics of green roofs in a tropical climate. The results confirm that a green roof is an effective heat preventing technique in a tropical climate. The overall lower temperatures of the underlying surfaces showed that green roofs reduce the heat load on a building. The high effectiveness of green roofs on days with a lot of sun hours prove that they act as a radiant barrier. Last a green roof reduces the temperature fluctuations of the underlying surface, which increases the durability of the material.

After the analysis a mathematical approach was used to quantify the heat prevention of a green roof. The results show that a green roof can prevent heat entering up to 1400 kJ/m^2 a day compared to a poorly insulated metal sheet roof. This reduction can also be expressed as an equivalent of the R-value. A green roof as studied has an equivalent of an R-value of 4.5 $K * m^2/W$. This is not the exact R-value of a green roof, because it not only works as an insulation technique, but also as a radiant barrier.

In the performed financial analysis, the costs and benefits of green roofs were compared in four scenarios. A local developed system was compared with a poorly and a medium insulated roof and a pre-fabricated system from Green Living Technologies was compared with a poorly and a medium insulated roof. The results show that a green roof can be profitable in a tropical climate in a life span of 20 years. The analysis also showed that the market for green roofs in Honduras is not yet developed, which can cause a price variation in the next decades.

Contents

1. Introduction

Green roofs are an ancient building technique and were already constructed in the days of Mesopotamia (Velazquez, 2005). In the last few decades they have made a re-appearance in the building sector. Green roofs have an ecological character and are especially useful in urban areas where they can oppose the effects of the current urbanization problems.

Nowadays green roofs are becoming more popular and their application is slowly spreading towards other areas than the starting point of the modern green roof building techniques, Europe. To spread the application of green roofs to new areas, their performances, characteristics and building techniques have to be tested in new circumstances. Therefore this research is dedicated to the tropical climate, where the use of modern green roofs still is in its infancy. Two characteristics of the area are important factors in the research; the use of metal sheet roofs instead of concrete slabs and the influence of the climate.

To study the use of green roofs in a tropical climate the following main question was formulated.

Which physical, environmental and financial benefits can be obtained with the application of a green roof in a tropical climate?

This question is too general to study in one research. To get significant results the research is divided in three main parts.

First of all a general picture is drawn of the building technique and possible benefits of green roofs. Thereby an analysis is made on the new challenges a tropical climate and the area of San Pedro Sula, Honduras brings to the use of green roofs. This study is done according to the first research question; *What is a green roof?* And can be read in Chapter 2.

In the second part the following research question is studied; *Is a green roof a effective heat prevention technique in a tropical climate?* To answer this question a practical study is performed. Experimental data is collected from two scale models in the local area, San Pedro Sula. In Chapter **Error! Reference source not found.** the test set up and research method is described and the results are presented graphically. These results have been quantified with a mathematical approach as can be read in the end of Chapter 4.

The last part presents the results of a financial analysis as a result of the third research question; *Is a green roof profitable?* The investment cost, the yearly maintenance and the financial benefits have been estimated in the local area, and can be read in Chapter 6.

1.1 Framework

Most of the current worldwide green roof performance research is based on a more or less specific design for concrete slabs in moderate climates. However, this study is dedicated to green roofs in a tropical climate on corrugated iron sheets. The difference in circumstances, the climate as well as the construction technique, creates a whole new situation. The experienced differences are mentioned in the next paragraphs to create a more clear vision on the environment of the research.

1.1.1 The climate

The climate has a big influence on the circumstances in which the green roofs are situated. The climate in San Pedro Sula (Honduras) can be described as tropical, which means a hot humid climate during most of the year. The mean temperature is in all twelve months well above 20 ^{o}C, with an average humidity of 87%. Seasonal changes are hardly noticed throughout the year. The difference in temperature is no more than 10 ^{o}C. The average annual rainfall is 2000 mm. In this area the heavy rains occur between September and December, however in other months rain events do occur.

The tropical climate gives a whole different perspective on designing techniques and material use. First of all, heating systems are unnecessary and therefore aren't available in any home or office building. In most 'passive' buildings (without use of full air conditioning) the inside temperature is more or less the same as the outside temperature. The challenge is to keep the inside temperature as low as possible.

The small difference throughout the year between inside and outside temperature provides the biggest challenge in preventing heat from entering the building and to immediately let excess heat flow out. The most heat entering a building will be from sunshine and radiation from surrounding buildings. To prevent this heat entering 'heavy' insulation is not the most used and neither the best solution, since excess heat is mostly let out the building through natural ventilation features. Techniques as increasing reflectivity (for individuals, but increases radiation of the building) or creating shadow are therefore more effective.

When full air conditioning is used (as is in most office buildings), the design needs to be different. Natural ventilation is not applied and extensive insulation will be necessary.

1.1.2 Slope

A sloped roof in comparison with a flat roof has several influences on the behavior.

1. Water will flow faster out of the layer of soil. Therefore the initial delaying time of rain runoff of sloped roof is smaller than flat roofs (Getter, et al., 2007).
2. The reduction of rain water runoff is smaller of sloped roofs in comparison with flat roofs (Getter, et al., 2007).

More information on rain water retention can be found in paragraph 2.4.2 Hydrology.

Above a slope of 20% the risk of sliding and the wash out of soil increases and additional measurements need to be taken. The green roofs used in this study do not exceed the percentage, thus this is out of the scope of the research.

1.1.3 Material used

Metal sheets are the most used roofing material in the area of San Pedro Sula. Most corrugated iron sheets are made of an alloy of aluminum and zinc, shortly referred to as aluzinc. Corrugated iron sheets have a very low insulation value (R-value, for more information see appendix A). This results in fast transportation of incoming as well as outgoing heat. A corrugated iron sheet is a good radiant barrier, which means it reflects a high rate of incoming (solar) radiation. High reflectivity is a good individual cooling technique, but it radiates heat to the surrounding area, which doesn't make it a good communal solution.

Concrete roofs have a higher insulation value (R-value) and have a high heat capacity. This means that most of the heat is absorbed by the concrete, transfers slowly through the concrete and it takes also time to release the heat back into the surrounding area. Concrete is therefore a better insulator than corrugated iron, but a bad radiant barrier unless painted in bright colors (Suehrcke, et al., 2008).

The effect of the two materials, concrete and metal, on the performance of a green roof is trivial. The difference in the material is more important with full sunshine (clear sky), but since a green roof is a shade provider this situation doesn't occur to the materials below it. It is expected that a building with a green roof on a concrete roof, in comparison with a green roof on a metal roof, will heat up more slowly but will cool down more slowly as well.

1.1.4 Vegetation

The plant selection is an elementary component of a green roof. In colder climates mostly different types of sedums are used. The tropical climate tough ask for another type of plants, since they cannot stand the heat or heavy rain falls. The criteria for the ideal plants include; heat resistance, drought resistance, rain resistance and growth control. The last criterion is especially of influence for maintenance requirements, since everything tends to grow faster in a tropical climate. The search for the ideal plant selection in a tropical climate has not yet ended. Therefore only considerations can be made.

2. Characteristics of green roofs

To better understand the use of a green roof a general picture of them is given in this chapter. The specific designs and materials of green roofs can vary by project, but every green roof has the same basic components. To start, my general definition of a green roof; a green roof is an engineered roofing system that allows vegetation to grow on top of a part of a roof or on the complete roof of a building while protecting the integrity of the underlying structure.

In this chapter the characteristics of green roofs will be discussed. First the functioning of a green roof is explained, the distinction between two types is clarified and the general building method is reviewed. Thereafter the environmental benefits are discussed.

2.1 Functioning of a green roof

When the sun radiates upon a roof this energy is either reflected back into the air or absorbed by the roofing material. Absorbed radiation energy is mostly transferred into heat and will enter the building beneath the roof. Reflected energy will warm up the surrounding area of the building and this heat can enter the building through other surfaces.

Green roofs on the other hand use a significant part of the radiated energy. The vegetation uses this energy for their biological functions such as photosynthesis. Only a small part of this energy is reflected back into the air or absorbed by the underlying materials. In Figure 1 an illustration is made of a house with and without a green roof.

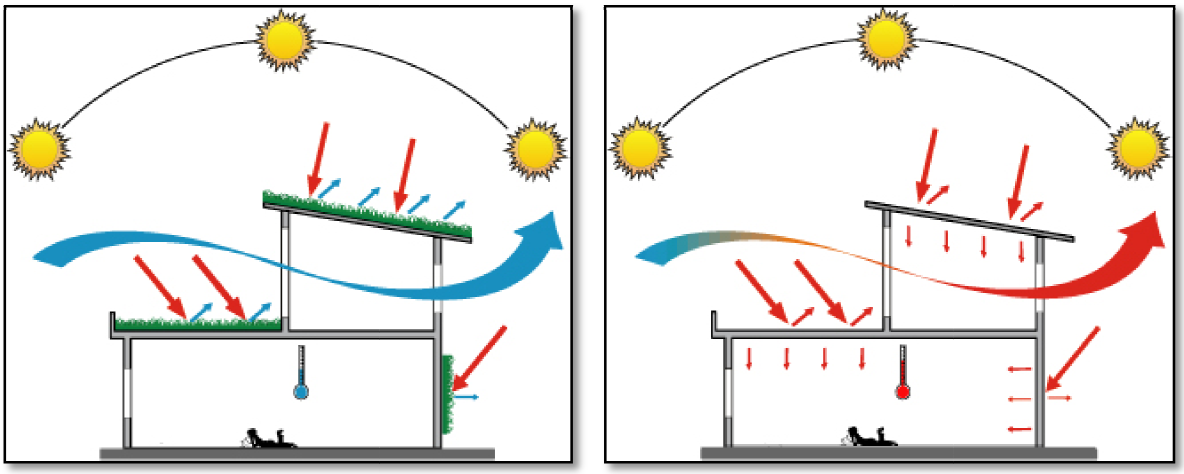

Figure 1: House with and without a green roof

2.2 Types of green roofs

Green roofs can be roughly divided into two categories: intensive and extensive green roofs. The difference between the two types will be explained in this paragraph.

2.2.1 Intensive green roofs

Green roofs are generally categorized on the depth of their soil layer. An intensive green roof has a soil layer of at least 6 inches (±15 cm) (O'Keefe, et al., 2008). Intensive green roofs – also referred to as roof gardens - contain a multitude of plant species and can even accommodate shrubs and trees. These varieties of plant species give opportunities for a more attractive design and therefore intensive green roofs are often installed as outdoor amenity space with the possibility of human occupancy (Earth Pledge, 2005).

Compared to extensive green roofs, the aesthetical design of intensive green roofs in turn require more regular irrigation and maintenance. Buildings featuring them also have to be able to bear the extra weight of the thick layer of soil and human occupancy (Earth Pledge, 2005). The higher structural roof capacity, the aesthetical design, the need for irrigation and maintenance require a higher initial investment and can increase the annual costs.

2.2.2 Extensive green roofs

Extensive green roofs, also known as ecoroofs or roof meadows, are often planted with short rooted drought resistant species (sedums) and grasses, which only require a layer of soil between 2 – 6 inches (±5 – 15cm). Special soil mixes, with for example crushed brick or lightweight aggregates, are used to reduce the weight. This makes an extensive green roof a lightweight construction (50-150 kg/m^2) (Earth Pledge, 2005; O'Keefe, et al., 2008). Most extensive green roofs are solely constructed for their ecological benefits and are not built for human occupancy.

An extensive green roof is the simpler and more cost effective of the two types and meets the goals of ecological design with their self-sustaining planting. This limits the need for irrigation and maintenance and reduces annual costs. The reduced weight of an extensive green roof often does not require adjustments of the construction beneath it. When the choice for a green roof is made in an early design stage the extra costs are minimal. This reduces the initial investment of an extensive green roof (O'Keefe, et al., 2008).

2.3 Construction layers

In spite of the different styles, designs and even construction methods almost all green roofs are made of six basic elements: waterproofing membrane, root barrier, drainage layer, filter fabric, growing medium and vegetation. These layers are shown in Figure 2 a short explanation per layer will be given in this paragraph to give a basic understanding of green roof design and construction.

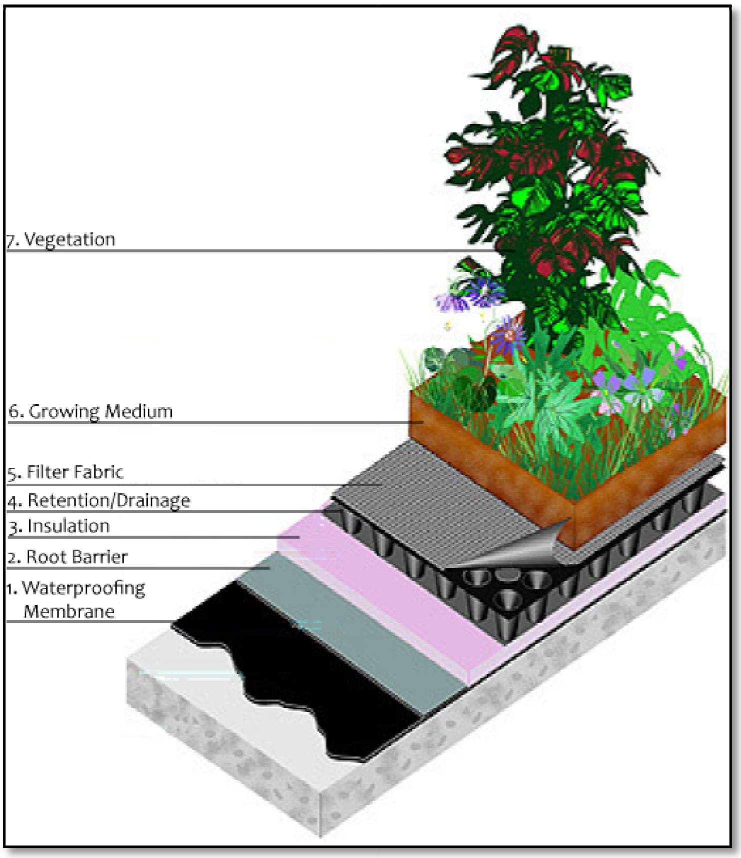

Figure 2: Layers of a green roof

1. Waterproofing membrane: A waterproofing membrane safeguards the roof from leakage and therefore is one of the most important elements of any roof – green or not (Earth Pledge, 2005). There are three types of waterproofing systems commonly used.

Modified bituminous membranes are made by fusing two organic felts with bitumen, a coal byproduct. Synthetic rubber is added to the bitumen for flexibility, elasticity and strength. The membrane is applied by torching down sheets to the roof deck, or spreading the liquid form.

Thermoplastic membranes are made of synthetic sheets rolled on the deck, overlapping at the joint and are applied with heat or mechanical fasteners. PVC, more commonly known as vinyl, is torched down to the roof deck.

Elastomeric membranes, such as EPDM, are made of synthetic rubber. They are strong and puncture-resistant. EPDM uses adhesive tabs to attach it to the deck.

2. Root barrier: The root barrier protects the waterproofing membrane and deck from penetration by aggressive roots. A polyethylene sheet serves as an effective root barrier or filter fabric inlaid with copper foil or copper hydroxide, as copper is a natural root repellant.

3. Insulation: Insulation is not a structurally necessary component of a green roof, but most building codes require it in standard roof construction to prevent heat loss. An additional insulation layer maximizes energy savings by reducing heat and air conditioning use. Insulation can be applied beneath the roof deck or between the waterproofing membrane and roof deck. Materials for insulation are numerous.

4. Drainage/Retention layer: The drainage layer prevents oversaturation, ensures that roots are ventilated and provides roots with extra room to grow. Many drainage layers also help retain water or are partnered with retention mats. Water can flow naturally of pitched roofs (over 5^o) making a drainage layer unnecessary except to aid with extra retention.

Synthetic drainage boards are usually made of strong, lightweight plastic and have different shapes (egg cartons, honeycombs).

Granular aggregate is made of a mineral mixture, such as clay, lava, expanded slate, slag, brick or foamed glass. This kind of base has been used as drainage for centuries and is often made from the primary components in the growing medium. It is heavier than synthetic drainage mats, but stores water more effectively.

5. Filter Fabric: *A geotextile filter fabric* must be placed between the drainage layer and the growing medium to keep the substrate in place. It is usually made of polyester or non-woven polypropylene.

6. Growing Medium: The growing medium for a rooftop is made from different components than ground soil – a mineral base with minimal organic material – and is therefore often referred to as *substrate*. A good green roof substrate is often a mix of a lightweight aggregate and organic matter. Low-weight, high-porosity aggregates like expanded shale and clay are particularly suited for rooftops and have stable grains that will not get windblown. Other common materials are expanded clay, expanded shale, crushed brick, lava and volcanic glass.

7. Plant Selection: A green roof would not be a green roof without vegetation. The selection of appropriate plants is essential to both the aesthetic and environmental function of the green roof. In most dry and cold locations a mix of sedums is common for extensive green roofs.

2.4 Environmental aspects

Building gardens on top of roofs is an environmental building technique especially suitable for areas with a high building density. In these areas more and more natural surfaces are covered by building materials such as concrete, metal and asphalt. This transduction of used materials influences the environment. Problems with impervious surfaces include higher ambient air temperatures, increased noise, increased storm water runoff, poorer water quality, poorer air quality and a loss of biodiversity.

Green roofs are one potential remedy for these problems. Establishing plant material on rooftops provides numerous ecological and economic benefits which makes it a multifunctional solution for the urban problems of the 21st century. Environmentally speaking there are no known disadvantages. The benefits include storm water management, energy conservation, mitigation of the urban heat island effect, increased longevity of roofing membranes, and mitigation of noise and air pollution, as well as a more aesthetically pleasing environment in which to work and live.

In the following paragraph each environmental beneficial aspect of a green roof will be described. In these descriptions previous published research is used. This literature is mostly based on extensive green roofs built upon flat concrete slabs. Studies based on warmer climates or summer periods were used where possible. Unless exceptions are mentioned, the literature used is based upon extensive green roofs on concrete slabs.

2.4.1 Energy conservation

The green roof energy performance and its thermal properties are subjects to which a lot of scientists led their research the last years. Unfortunately, much of the current field monitoring and computational modeling is referenced to cold climate designs and performance. Because this research is dedicated to a tropical environment, only analyses in warm climates or during summer periods are used.

It has been shown that a well designed and managed green roof could behave as a high quality insulation device in summer (Barrio, 1998). Thereby in some circumstances the green roofs even works as a passive cooling technique, which means it transports heat out of a building (Lazzarin, et al., 2005).The energy performance depends on the type of vegetation, the type of soil, the moisture content, the outside temperature, the humidity and the solar radiation (Theodosiou, 2003; Lazzarin, et al., 2005).

The layer of soil in a green roof reduces the thermal conductivity of the roof, thereby increasing the insulation. The thickness of the soil layer, its apparent density and its moisture content determine the soil thermal conductivity. It increases with the apparent density and decreases with the soil moisture content (Barrio, 1998).

The most important function of the vegetation is providing shadow to the roof. This provides a great degree of reduction in the local air temperature near canopy, thus reducing the incoming heat flux into the building (Kumar, et al., 2005) and protects the roof from direct solar radiation (Niachou, et al., 2001). But the vegetation has numerous other advantages. It reflects more sunlight than a traditional concrete roof, which prevents heat gain into the building. The plants absorb a significant proportion of the solar radiation for their biological functions, such as photosynthesis, respiration and transpiration (Barrio, 1998). Thereby the extra water captured in either the soil or the vegetation enhances cooling by evaporation (Onmura, et al., 2001). This makes the amount of saturation of a green roof an important factor in the behavior of a green roof. Other factors are: the type of vegetation, the type and thickness of the soil, the outside temperature, the humidity and the solar radiation (Barrio, 1998; Theodosiou, 2003; Lazzarin, et al., 2005).

In Figure 3 a comparison of energy transfers is made between a traditional concrete roof, a dry green roof and a wet green roof and the behavior in sunlight.

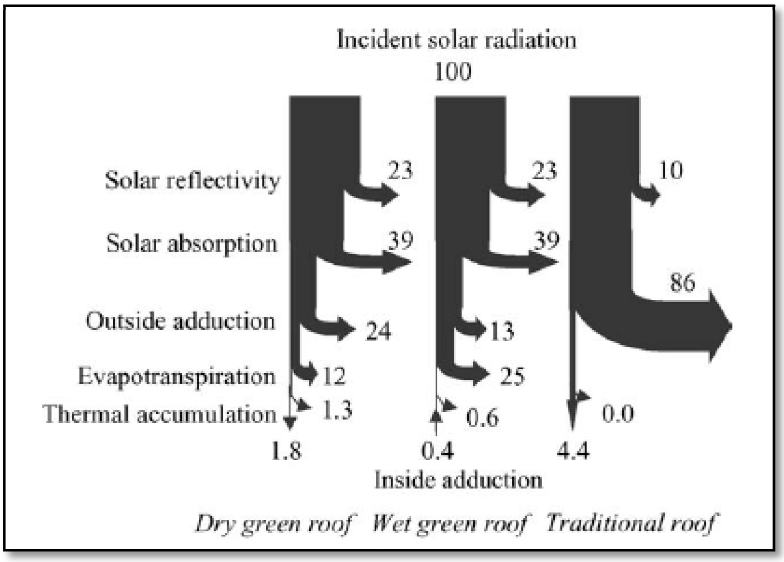

Figure 3: Comparison of the energetic exchanges (Lazzarin, et al., 2005)

The quantification of the energy conservation by green roofs is harder to define, because it is highly dependent on the materials used and the circumstances it is in.

Niachou, et al (2001) found that the difference, in the same building with and without green roof, in the mean inside air temperature of a building was 2^{o}C and the difference in maximum air temperature was 3^{o}C. The greatest savings during a whole year period were 37% compared to non-insulated buildings, but compared to medium and well insulated buildings the savings were respectively 4% and 2%.

Lazzarin, et al (2005) measured an attenuation of the thermal gain entering the underneath room of about 60% with respect to a traditional roofing with an insulating layer in a summer period. While Onmura, et al (2001) found that the surface temperature of the roof slab decreased from 60^{o}C to 30^{o}C during day time, which was estimated to be followed by a 50% reduction in heat flux into the room by simple calculation.

2.4.2 Hydrology

Storm water retention

Rainfall is often problematic in urban areas. Impermeable materials, like concrete, metal and asphalt, collect rainwater and direct it into the urban drainage system (Teemusk, et al., 2007). This results in a rapid run off, high peak flows and a reduction of infiltration in groundwater systems. Since more and more surfaces in urban areas are made of impermeable materials, the peak flows become higher and increases the potential of flooding (Getter, et al., 2007).

Green roofs are a potential solution for runoff problems in urban areas. They reduce the rainwater runoff by capturing the precipitation in the media or vegetation. The reduction consists in delaying the initial time of runoff due to the absorption of water in the green roof, reducing the total runoff by retaining part of the rainfall and distributing the runoff over a long time period through a relatively slow release of the excess water that is stored in the substrate layer (Mentens, et al., 2006). Eventually most of the retained water evaporates from the soil surfaces or is released back into the air by transpiration (Getter, et al., 2007).

The amount of rainwater retention depends on many factors, such as the volume and intensity of the rainfall, the amount of time since the previous rainfall event, the dept and wetting scale of the substrate layer, the slope of the roof, the plant selection, the ambient air temperature and the local environmental conditions on evapotranspiration, the sum of evaporation and plant transpiration (Mentens, et al., 2006; Getter, et al., 2007; Teemusk, et al., 2007).

Getter, et al (2007) measured rainwater retention on extensive green roofs with a substrate layer of 6 cm and a slope of respectively 2%, 7%, 15% and 25%. The green roofs retained an average of 80.2% of all precipitation averaged across all slopes and rain categories. Retention was highest in light rain events (<2mm) with 94.2% and lowest in heavy rain events (>10mm) with 63.3%.

Water quality

A green roof has a considerable effect – both positive and negative – on the quality of runoff water. The substrate layer of a green roof can work as a filter for rain water runoff clearing out different kinds of pollutions. However the green roof can also contain pollutions because of the use of fertilizers. The effect of a green roof depends on the character of the runoff: the slower the runoff rate, the higher the concentrations of total N, NH4-N and organic material. Heavy rain washed more phosphates and nitrates out of the green roof. The green roof generally acts as a storage device: pollutants are accumulated in the substrate layer and released when intensive rainwater washes them out. Although it is found that green roofs have both negative and positive effects, in terms of water quality green roofs definitely have more positive than negative effects, and they play an important role in improving the quality of the urbanizing environment (Teemusk, et al., 2007).

2.4.3 Air pollution

In metropolitan cities the air quality is often in a poor condition. The air contains high levels of pollutants that are harmful to human health. The World Health Organization estimated that worldwide, more than 1 million premature deaths annually could be attributed to poor air pollution in developing countries (World Health Organization, 2002).

Convenient air pollution management mostly focuses on controlling the sources of air pollutants. This strategy effectively reduces the emission of air pollutants, but does not address the pollutants already in the air. New approaches can be adopted to reduce air pollution to an acceptable level. A way to reach this goal is bringing back urban vegetation into cities. The high surface area and roughness provided by the branches, twigs and foliage make vegetation an effective sink for air pollutants (Yang, et al., 2008). Vegetation also lowers the ambient air temperature by changing the amount of reflected radiant energy of urban surfaces and evapotranspiration cooling. The lowered ambient temperature then slows down photochemical reactions and leads to less secondary air pollutants, such as ozone (Akbari, 2002).

In (Yang, et al., 2008) the level of air pollution removal by green roofs in Chicago was quantified using a dry deposition model. The results showed that the annual removal per hectare of green roof was 85 kg ha^{-1} yr^{-1}, with O_3 accounting for 52% of the total, NO_2 (27%), PM_{10} (14%) and SO_2 (7%). These results were dependent on the concentration of air pollution, length of growing season and meteorological conditions. This could result in different results among cities.

2.4.4 The Urban Heath Island Effect

The term "heat island" describes built up areas that are hotter than nearby rural areas. The annual mean air temperature of a city with 1 million people or more can be 1–3°C warmer than its surroundings. In the evening, the difference can be as high as 12°C. Heat islands can affect communities by increasing summertime peak energy demand, air conditioning costs, air pollution and greenhouse gas emissions, heat-related illness and mortality, and water quality (Environmental Protection Agency, 2008).

The development of urban heat islands is inhibited by two main factors. First in urban areas vegetation is more and more replaced by building surfaces. The materials used in buildings as concrete- and asphalt have different thermal properties and radiative properties than vegetation. These surfaces absorb the sun’s heat causing surface temperatures to rise. On the contrary, vegetation inhibits cooling through evaporation. The density of buildings changes the energy balance of the urban area, often leading to higher temperatures than surrounding rural areas (Weng, et al., 2004; Rosenfeld, et al., 1998). The secondary contribution is waste heat generated by energy use.

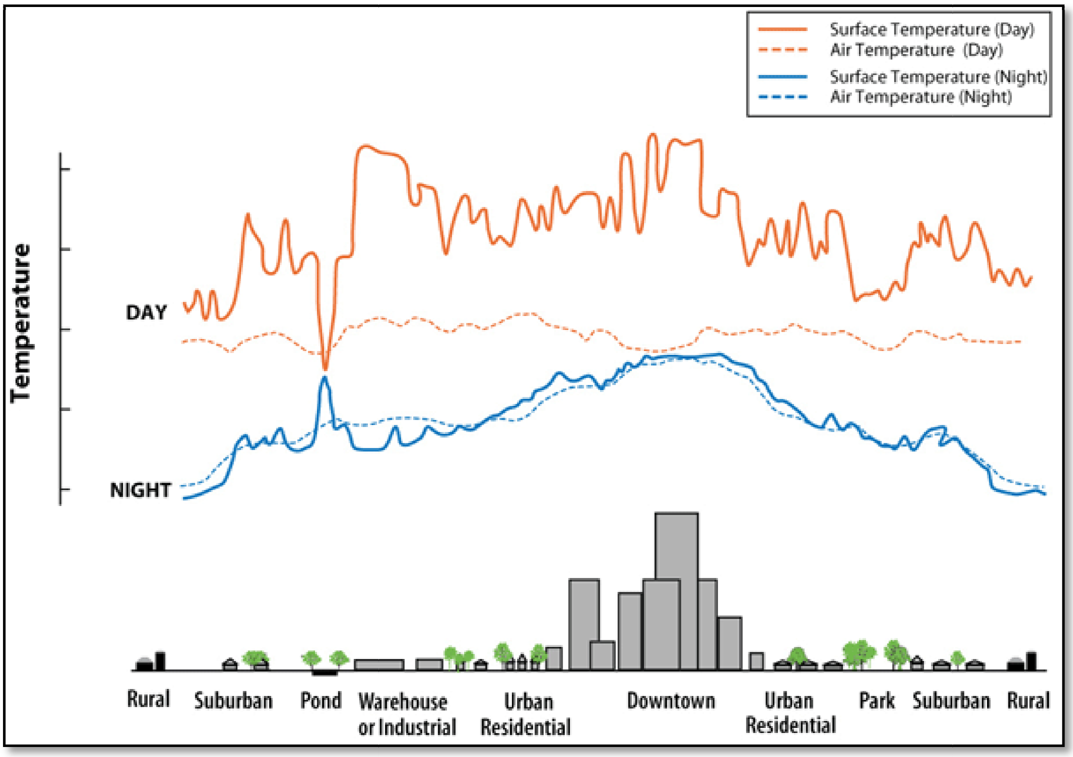

Figure 4: Sketch of an Urban Heat Island Profile (Environmental Protection Agency, 2008)

A promising option for dense urban settings and the mitigation of heat island effects is the greening of buildings (Johnston, et al., 1995), by example with creating more green roofs in cities. They are a solution to both of the contributors of the heat island effect. Green roofs increase the percentage of greenery and therefore bring flora as well as fauna back into urban areas. Thereby they contribute to the energy conservation in buildings as described in the previous paragraph.

There seems to be little controversy in the existence of the urban heat island effect. There is no controversy about cities generally tending to be warmer than their surroundings. What is controversial about these heat islands is whether, and if so how much, this additional warmth affects the global temperature record. The current state of the science is that the effect on the global temperature record is small to negligible.

Scientists compiling the historical temperature record are aware of the urban heat island effect, but they vary to how significant they think it is. Some scientists (Peterson, 2003) have published peer reviewed papers indicating that the effect of the urban heat island effect has been overestimated, and that it does not affect the record at all. Other scientists have used various methods to compensate for it. Some supporters charge that temperature data from heat islands has been mistakenly used as evidence for the global warming theory.

3. Sub conclusion

In conclusion, the two main types of green roofs are intensive and extensive green roofs. The first has a thicker layer of soil and gives more room for different kinds of vegetation and designs. Extensive green roofs are more developed for their ecological benefits and their economical character. Although green roofs differ from type, design and project the used construction consists general of the same six layers: waterproofing membrane, root barrier, drainage layer, filter fabric, growing medium and vegetation.

The benefits the construction of green roofs has are numerous. Some are beneficial for solely the user of the building while most of them effect the entire environment of the area. With the construction of green roofs the problems of urbanization can be counteracted.

The framework in which this research has been done brings a complete new situation. Instead of designing green roofs upon a flat concrete slab in a more or less cold climate, this research is dedicated to green roofs on inclined corrugated iron roofs in a tropical climate. This requires some considerations in the use of theory.

4. Experimental research

The practical part of this study uses experimental data collected from two scale models in San Pedro Sula, Honduras, in a tropical climate. With these models the influence of a green roof on the energy conservation in a building is simulated. The test set up, the materials used, the environment and the method of measurement is described in the following paragraphs.

4.1 Research design

4.1.1 Study area

The city of San Pedro Sula is located in Honduras, Central America as seen on Figure 5 . Its geographical coordinates are: 15° 30' North, 88° 2' West. The city’s elevation is 83m. With over 1.0 million citizens, San Pedro Sula is the nation’s 2nd largest city and known as the industrial capital of Honduras, due to its many factories, plantations and businesses concentrated around the city. The urban area of San Pedro Sula is 136 km^2 (Wikipedia inc., 2008).

Figure 5: Map of Central America

The climate in Honduras is tropical. Köppen scheme of climate classification defines it as a non-arid climate in which all twelve months have mean temperatures above 18°C (Köppen, 2008). Seasonal changes are hardly noticed throughout the year, except for rain events. The difference in temperature is no more than 10 °C. The average annual rainfall is 2000 mm. In the area the heavy rains occur between September and December, however in other months rain events do occur.

4.1.2 Test set up

In September 2008 two identical boxes were constructed of plywood in the residential area 'el Barrial'. The boxes were made air tight as good as possible by making the connections with nails and glue. All sides of the boxes, except for the roof, were insulated on the inside with a ¾ inch of Styrofoam with a R-value of 3.75 m^2K/W, to reduce the in and outgoing heat flow. A drawing of the identical boxes with sizes is shown in Figure 6. This test plot was designed to isolate the impact the green roof on the box temperature. Two different types of roofs were constructed on the boxes:

Box N: A 'normal' roof of corrugated iron was directly screwed on top of the box; the holes were made air tight with glue. The iron sheet is made of 60% aluminum and 40% zinc, the R-value of the sheet is negligible. The corrugated iron sheet was slightly bigger (1 inch on every edge) than the footprint to protect the box from rain. Figure 7 is a picture of Box N.

Box G: A green roof was constructed on top of the 'normal' roof. The layers of the total roof were from bottom to top: corrugated iron sheet, metal edging, ¾ inch Styrofoam, black industrial plastic, geotextile, soil and grass. The corrugated iron sheet was slightly bigger than the footprint of the box. The green roof was exactly the size of the footprint of the box. The depth of the soil layer is approximately 1 inch. The grass is named San Aguistin. A picture is shown in Figure 8.

The boxes were placed on grassland with their slope (13%) facing south. Both roofs were under direct sunlight from the rise of the sun 5.30 until approximately 16.00 when they were in the shadow of the surrounding buildings.

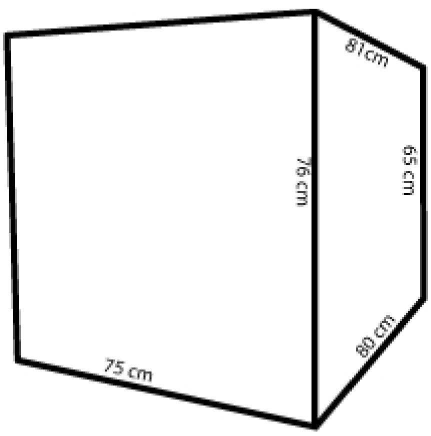

Figure 6: Drawing of the used boxes

Figure 7: Test box N

Figure 8: Test box G

In both boxes two thermocouples were placed. The first was placed inside the box in the center of the roof, 15 cm beneath the roof. These thermocouples measured the inside temperature of the boxes. The second thermocouples were placed on the metal sheets of the boxes. They were placed in the center of the roof, under the metal sheets. These thermocouples measured the temperature of the metal sheets. A fifth thermocouple was placed on a windless place in the shadow, to measure the outside temperature. The thermocouples are made of chromel - alumel.

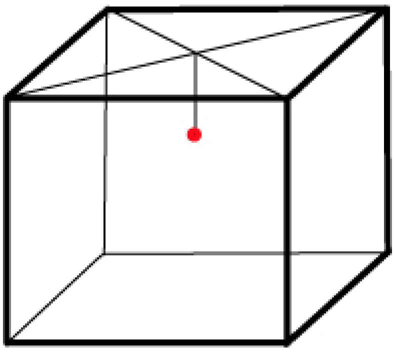

Figure 9: Location of the first thermcouple

All five thermocouples were connected to a datalogger of National Intsruments type NI USB-6218. This apparatus was connected to a computer with Labview Signal Express Software v.x.t. Measurements were recorded for 11 days from at least 8.30 until 17.00 every second. To protect the measurement equipment, measurements could not be taken under all circumstances; therefore measurements were only taken on days without rain during all hours. The measurements were taken on days with partial or entire day of sunshine. On 15 November measurements were taken on a full clouded day with some rain events. On 6 October measurements were recorded for 24 hours, to analyze the behavior during the night. According to NASA, 2008 17% of all days are fully clouded or have rain during all hours of the day. These days were not taken into account in this research.

4.2 Collecting experimental data

More detailed conclusions of the impact of the green roof on the outdoor and indoor conditions can be made from a thorough analysis of the measured data, recorded by the temperature sensors in the boxes. Analyses have been done on all available measurement data. In this chapter the results are shown graphically. The graphs shown in this paragraph are the results of 7 October. This day has been chosen because it shows certain behaviors of the green roof in a clear way. Thereby the behavior of the roofs on 7 October is similar to the behavior of all other days with partial or full sunshine. This behavior is studied with the graphical results in combination with logbooks made of these days. The graphical analyses and a short description of the logbook of the other days can be found in Appendix E.

4.2.1 Average temperature

The temperature measurements in all thermocouples were taken every second. These measurements were averaged over every half hour. The average temperature of all measurement points on 7 October are presented in Chart 1. In Chart 2 the original data (without averaging) is shown of the morning of 7 October.

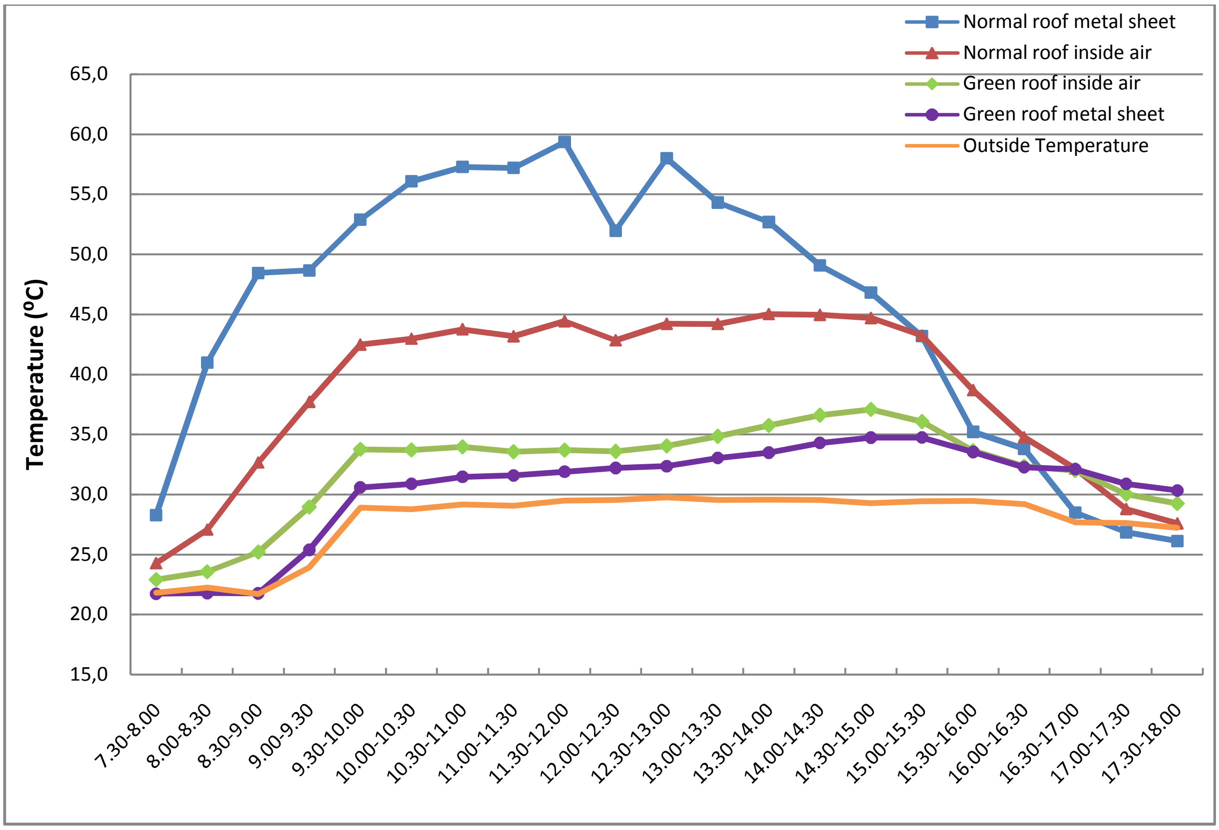

Chart 1: Average temperature

Chart 1 let us see some interesting results. It is striking that average inside air temperature of Box G is lower, compared to Box N, during all hours in which the sun radiates upon the roofs. The only time when the inside air temperature of Box G is higher is in the late afternoon, shortly after both boxes are in the shadow. This indicates that Box G cools down slower than Box N; this can be due to a higher insulation value or a higher heat capacity of the green roof, because for the rest they are identical.

The fast reaction of the normal roof to sun radiation is even more extreme in the metal sheet temperatures. In the morning the bare metal sheet warms up quicker than the metal sheet with a green roof. Thereby it also cools down faster in the late afternoon. This indicates that a green roof causes a time delay in the reaction of the metal sheet on sunshine.

The fact that the inside air temperature of box G is higher than the temperature of the metal sheet signifies that a green roof not only prevents heat gain into a building but also can release heat back into the air. The walls of the box warm by incoming sun radiation. The green roof releases this heat back into the air. However this is also due to the relative high temperatures of the boxes because of making the box air tight.

During the day temperature fluctuations of both the inside air and the metal sheet temperature are more intense in Box N. By making a logbook on two specific days, it was found that the metal sheet temperature reacts very fast on two influences, sun radiation and wind. In case of a sudden gust of wind the temperature of the bare metal sheet drops immediately 2 ^{0}C to 3 ^{0}C. The change due to sun radiation is visible between 11.30 and 12.30 where a longer time sun radiation was blocked by clouds. The metal sheet temperature of Box N dropped fast, while the temperature change in the metal sheet of Box G is barely visible.

The rapid change of temperatures of the metal sheet of Box N is also clearly visible in Chart 2, where the temperatures have not been averaged. It can be seen that the temperature variations are faster and more intense during the day.

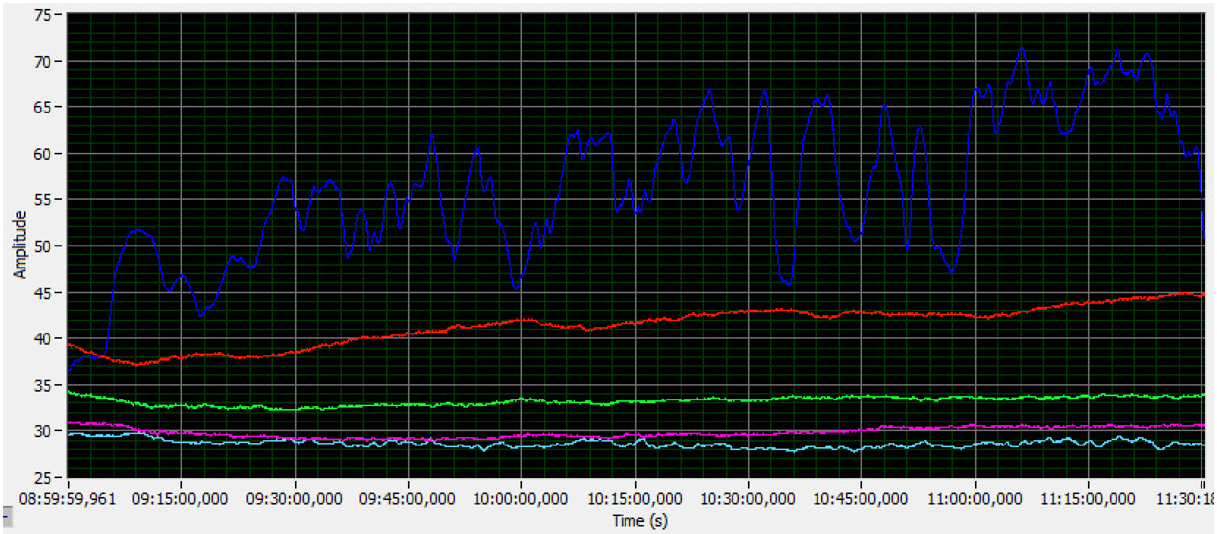

Chart 2: Temperature per second

4.2.2 Classification of temperatures

The whole set of data records have been categorized in to temperature scales of 5 ^{o}C. The measurements were taken every second and every measurement during one day is placed into the categories. The graphs of this categorization on the specific day of 7 October between 7.30 and 18.00 are shown in Chart 3 and Chart 4.

Chart 3 shows that the data of the inside air temperature of Box N are more in the higher part of the categorization, while the inside air temperature of Box G stays in the lower regions. For example, it is visible that for the whole set of records in Box N 70% of the inside air temperature measurements have exceeded the value of 35^{o}C, in contrast with the inside air temperature measurements of Box G of which only 21% exceeded the value of 35^{o}C.

In Chart 4 the same analysis is shown for the metal sheet temperature values of both boxes and even higher rates are found. Of the measurements of the metal sheet temperature of Box N 78% exceeded the value of 35^{o}C. While of the metal sheet temperature of Box G only 3% of the measurements exceeded the 35^{o}C value.

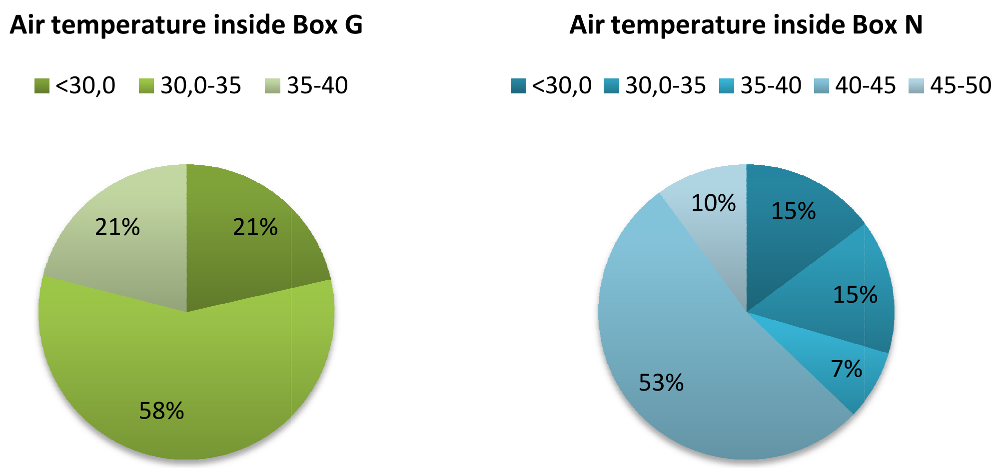

Chart 3: Classification of air temperatures

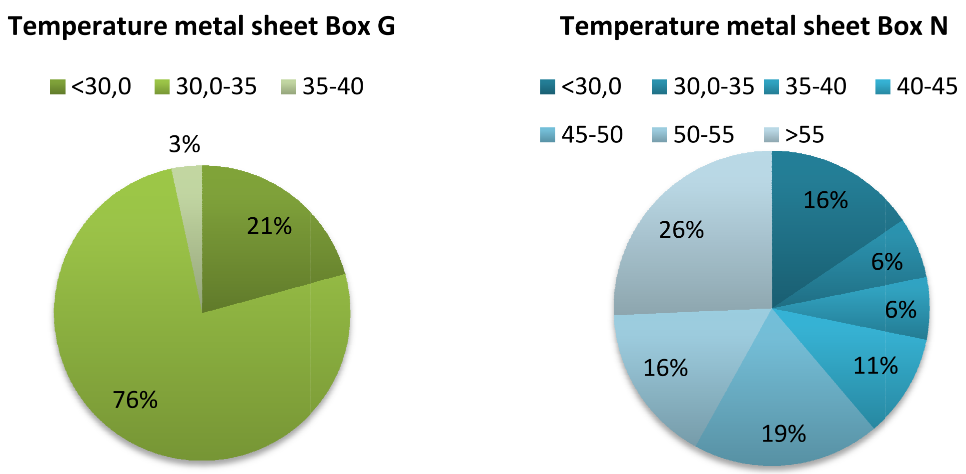

Chart 4: Classification of metal sheet temperature

The overall lower temperature during daytime of the green roof metal sheets indicates that the heat load on Box G is lower than the heat load on Box N. This means less heat is pressing on the building and less heat is therefore expected to enter the building. This is eventually visible in the inside air temperature of the boxes. Box N has overall a higher inside temperature than Box G.

4.2.3 Temperature differences

Regarding the absolute temperature range within the boxes, the difference between the absolute minimum and the absolute maximum, the temperature fluctuates less in both the inside as the metal sheet temperature of Box G. The inside air temperature of Box N had a range of 24.2 ^{o}C on 7 October, while the inside air temperature of Box G only had a range of 16.8 ^{o}C. The metal sheet temperatures were fluctuating 48.4 ^{o}C for Box N and 14.8 ^{o}C for Box G.

The fluctuations in temperature stress the materials used, because of expansion and contraction influenced by the temperature difference. Therefore it indicates that materials underneath a green roof can have a longer life span. But the influence of other factors as water, enhanced corrosion or damage to the top coat of iron sheets by a green roof will maybe shorten the life span.

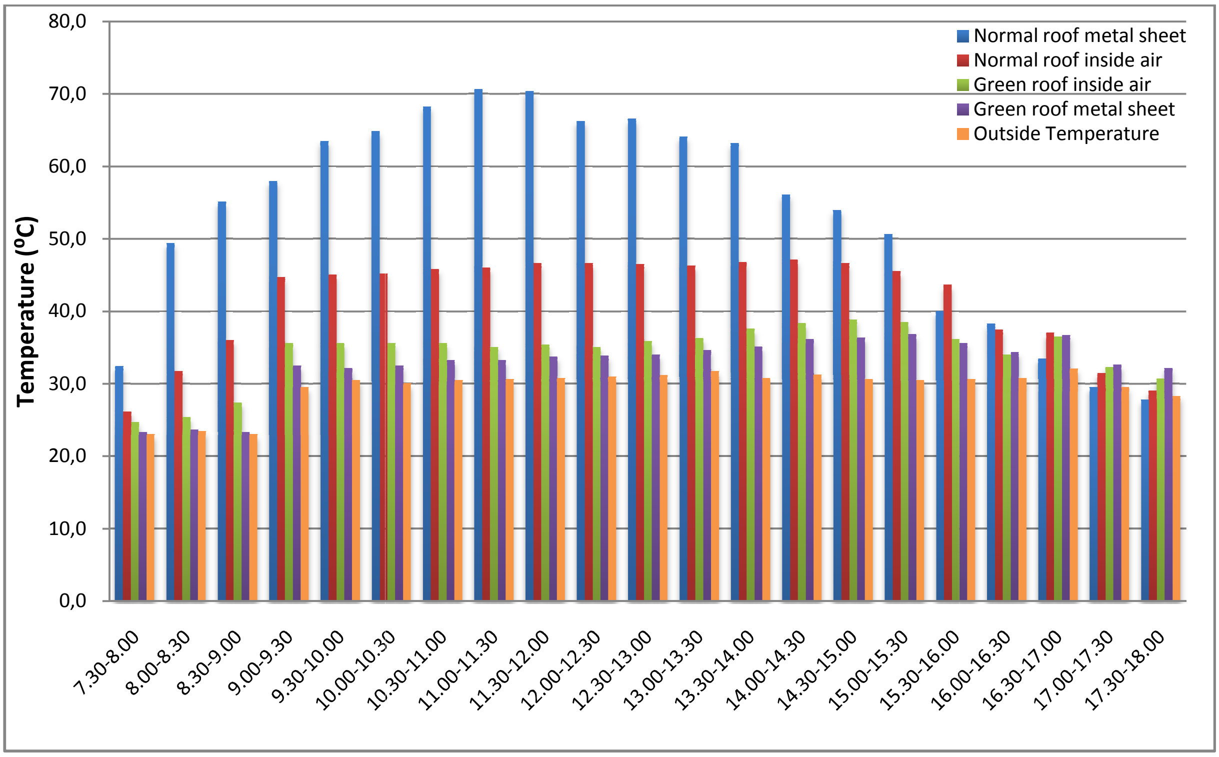

Chart 5: Maximum temperatures

The temperature differences between both boxes are shown in Chart 6. This graph shows that the differences between both boxes are higher in the hours of sun radiation and are the highest around midday when the sun radiates straight on the roof. The differences reduce when the sun loses its force at the end of a day. This shows that a green roof is most effective in hours of sun radiation.

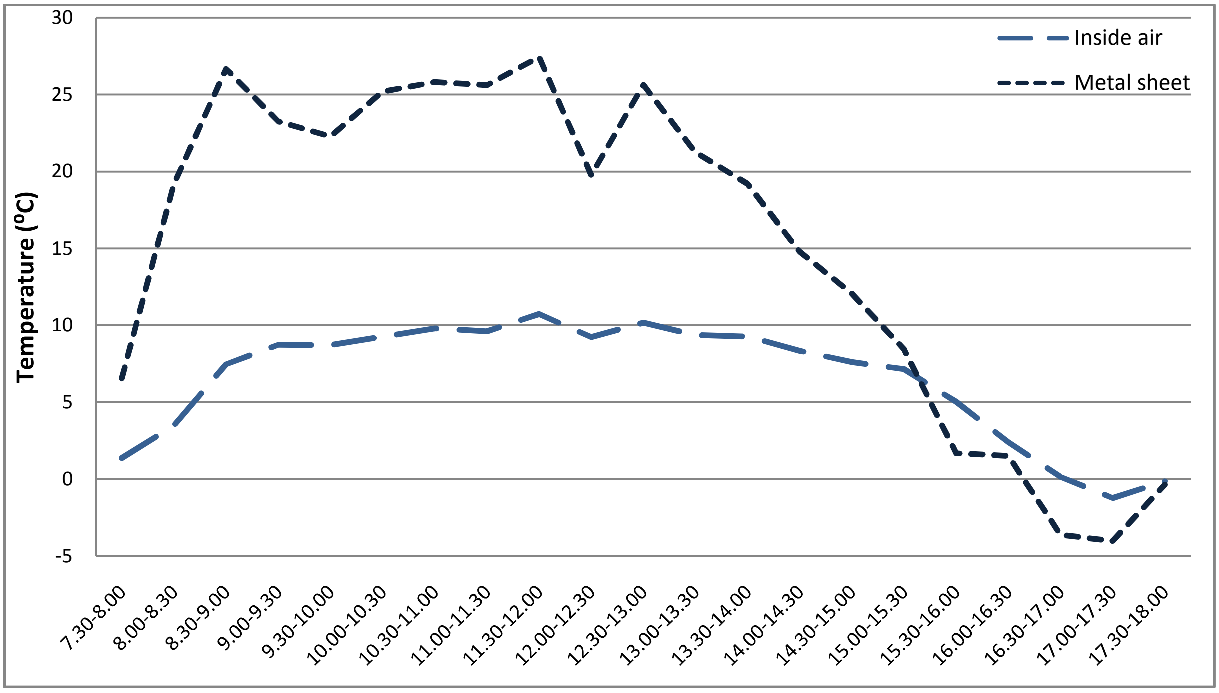

Chart 6: Temperature difference

The conclusion that a green roof is most effective in hours of sunshine is evident when compared to a day without sunshine. On 15 November measurements were taken on a fully clouded day with some mild rain events. In Chart 7 the average differences between both boxes are shown of all measurement days. The difference between the two boxes on 15 November is minimal compared to the other days. It can mean that a green roof is a good radiant barrier. A radiant barrier is a material that inhibits heat transfer by thermal radiation (Wikipedia inc., 2008). Radiant barriers slow down heat flow by two means - by reflecting radiant energy away from its surface or by reducing the emission of radiation from its opposite side (Suehrcke, et al., 2008). Green roofs act probably as a radiant barrier by using radiation energy for biological functions of the plants. A good radiant barrier does not have to be a good insulator.

	Inside air (ºC)	Metal sheet(ºC)
6-okt	5,33	12,60
7-okt	7,28	16,18
8-okt	5,20	11,85
9-okt	7,65	16,68
10-okt	7,54	20,28
13-okt	7,60	17,38
14-okt	3,38	7,45
5-nov	4,71	12,87
12-nov	4,42	9,98
13-nov	5,08	10,22
14-nov	6,71	13,01
15-nov[1]	0,13	0,73

Chart 7: Average temperature differences between Box N and Box G

[1] Full rainy day

4.3 Analyzing collected data

In order to quantify the thermal properties and to evaluate their performances a mathematical approach is used on the results of the experimental measurements. The mathematical approach is used to calculate the energy conservation of a green roof compared to a corrugated iron sheet roof.

4.3.1 Energy transfer

To calculate the energy performance of an extensive green roof the law of energy conservation is very important. In an isolated area this law states that energy cannot be created or destroyed; it can only change its form. Therefore the energy inside the model boxes can be expressed as

$$\Delta E = E_{in} - E_{out} \tag{1}$$

in which E_{in} is the total heat gain, E_{out} is the total heat loss and ΔE is the change of energy in the box due to temperature difference. The flow or transfer of heat inwards or outwards the boxes will take please in one or any of the following three methods.

Conduction: Heat energy is transferred directly through materials in contact with each other, where a temperature difference exists. Heat transfer along a metal rod is a simple example of conduction.

Convection: Air, when heated, becomes less dense than the surrounding air and raise upwards. The denser and cooler air flows downwards. These air movements, known as convection currents, can occur in spaces between the framing members of ceilings or walls of buildings causing a significant amount of heat loss.

Radiation: Heat energy may be radiated across the air space and then be absorbed by another body. Radiant energy from the sun is an example, where this energy may be absorbed as heat by the human body.

The assumption is made that convection doesn't occur in the boxes. Heat is only transferred through conduction or radiation. Therefore the incoming or outgoing heat flow is caused in two ways:

- Temperature differences between the outside and inside temperature (conduction)
- Solar radiation being absorbed on a surface (radiation)

The exposure of surfaces to solar radiation increases the surface temperature and sets up a heat flow in parallel to the one set up by temperature difference. The effect of solar radiation absorption is usually the most important factor for the daytime downward heat flow from a roof surface in a hot climate (Akbari, 2002). But it should be noted that the solar absorptance of a roof is not the only variable influencing roof and air temperature.

4.3.2 Daily heat gain

Through conduction the heat inside the boxes will try to flow from a warmer area (inside) to a colder area (outside). This process takes place through the walls as well as the roof. The amount heat loss depends on the insulation of the walls and roofs their surfaces and the temperature difference between the inside and ambient air temperature. The total heat loss can be described as

$$E_{out} = (U_{walls} * A_{walls} + U_{roof} * A_{roof}) * (T_i - T_a) \tag{2}$$

where U is the overall heat transfer coefficient (inverse of the R-value), A is the surface of respectively the walls and the roof and $(T_i - T_a)$ is the difference between the inside and ambient air temperature. For a clear understanding of the thermal resistance value (R) and the overall heat transfer coefficient (U) an explanation is written in Appendix A.

The R-values of the materials used in the boxes are presented in Table 1 (Wikipedia inc., 2008). R-values of different layers can be added to calculate the total R-value of a cross-section. U can be calculated by $U = \frac{1}{R}$. The conservative assumption is made that a green roof does not increase the insulation value of the constructed roof, therefore it has an R-value of 4. The characteristics of the different parts of both boxes are presented in Table 2.

Material	R-value (m^2K/W)
Plywood 3/8"	0.47
Styrofoam 3/4"	3.75
Metal sheet	Neglected

Table 1: R-values of used materials

	R-value (m^2K/W)	U (W/m^2K)	A (m^2)
Box N			
Walls	3.75 + 0.47 = 4.22	0.237	2.12
Roof	0.47 + 0 = 0.47	2.13	0.64
Box G			
Walls	3.75 + 0.47 = 4.22	0.237	2.12
Roof	4	0.25	0.64

Table 2: Characteristics of the boxes

With these characteristics the total heat loss of the two boxes can be calculated.

$$E_{out,N} = (0.237 * 2.12 + 2.13 * 0.64) * (T_i - T_a) = 1.87\ W/K$$

$$E_{out,G} = (0.237 * 2.12 + 0.25 * 0.64) * (T_i - T_a) = 0.66\ W/K$$

The temperature difference between the inside and ambient temperature can be derived out of the measurement results. Of these results the average difference is calculated, during the time that sun radiates on the roofs. It is assumed that during the time the sun does not radiates upon the roof the temperature difference is 0. Therefore heat loss only takes place 12 hours a day. This heat loss represents the heat loss of a green roof of 0.64 m^2. To calculate the heat loss per m^2 the heat loss is divided by 0.64.

The heat loss is first calculated in Watts. It is recalculated to kJ/day, with $1\ W = 1\ J/s$ and one day has $12 * 3600 = 43200\ s$.

	E_{out} (W/ΔT)	$(\boldsymbol{T_i - T_a})$	E_{out} (W)	E_{out}(kJ)	E_{out} (kJ/m^2)
Box N	1.87	12.5	23.38	1009.8	1577.8
Box G	0.66	4	2.64	114.0	178.2

Table 3: Daily heat loss

The total daily heat loss of the boxes is:
Box N: 1577.8 kJ/m^2
Box G: 178.2 kJ/m^2

The heat change inside the box is calculated by

$$\Delta E = V * Q * \Delta T \tag{3}$$

in which Q is the specific heat of air 1,29 kJ/m^3K and V is the volume of the box. This results in a change of energy of respectively 6.2 kJ for Box N and 2.1 kJ for Box G.

With the values of the total daily heat loss and the change of energy inside the box the total daily heat gain through the roofs can be calculated with a different form of equation (1) as stated in the beginning of the chapter: $E_{in} = E_{out} + \Delta E$.

	E_{out} (kJ)	ΔE (kJ)	E_{in} (kJ)
Box N	1577.8	6.2	1571.6
Box G	178.2	2.1	176.1

The daily heat gain of the green roof is 1395.5 kJ less per square meter compared to a poor insulated metal sheet roof.

4.3.3 Exertion for calculation of corresponding R-value

The daily heat gain of a green roof is 1395.5 kJ less compared to a poorly insulated metal sheet roof. This conservation is made through two major factors. First of all the insulation value of a green roof can be higher than a metal sheet roof. Second the solar absorption of a green roof can be lower than the metal sheet roof. The difference between the two systems will be explained and quantified in this section. But be aware, an exact division between the two factors cannot be made, because of a lack of information. Therefore the quantifications of both values are only estimations.

An analysis of the daily heat gain of a roof can be made with the steady state heat transfer rate. For more information of the steady state temperature of a surface see Appendix C. Although a roof does not experience a steady state while temperatures and radiation are changing, because the thermal mass causes a significant time lag in the temperature response. In this research only a particular aspect of the effect of thermal mass is of interest, the influence of the roof thermal mass on the integrated daily heat gain.

The results of a numerical simulation performed by (Suehrcke, et al., 2008) suggest that the integrated daily heat gain from the roof into a building is nearly independent of roof thermal mass. This is an important result for this study as it suggests that the integrated daily heat flow from an unventilated roof can be calculated without considering heat capacitance effects. This means a simplification of the used formulas.

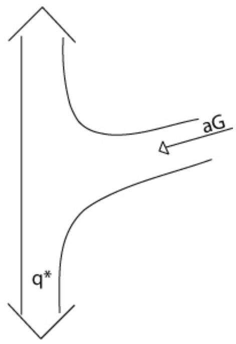

Figure 10: Heat flow into roof

For steady state the solar radiation absorption on the roof surface changes the heat flow to the outside and the inside environment as shown in Figure 10. Using this thermal network the steady state heat flux (q) that flows into a building can be found by

$$q = U\left[(T_a - T_i) + \frac{\alpha G}{h_0}\right]$$

(4)

where U is the overall heat transfer coefficient also stated as the inverse of the R-value, $T_a - T_i$ the ambient to inside temperature difference, α the roof surface solar absorptance, G the solar irradiance and h_0 the roof to ambient heat transfer coefficient. For the derivation of Equation (4) see Appendix D.

In order to judge the benefit of a green roof on the heat gain from a roof it is required to calculate the heat flow due to both temperature difference and solar radiation over a whole day by integrating Equation(4) over a whole day.

$$= \int_{day} U \left[(T_a - T_i) + \frac{\alpha G}{h_0} \right]$$

$$= U \left[\int_{day} (T_a - T_i)\, dt + \frac{\alpha}{h_0} \int_{day} G dt \right]$$

$$= U \Delta t \left[\Delta \bar{T} + \frac{\alpha}{h_0} \bar{G} \right]$$

(5)

where $\Delta \bar{T}$ is the average daily temperature difference between outside and inside, $\bar{G}$the average daily solar radiation, Δt the day length in seconds (24x3600s). With the assumption that U and $\frac{\alpha}{h_0}$ are constant.

For the calculation of the average daily heat gain several quantities are required.

Average daily temperature difference: For non air-conditioned buildings the inner temperature tends to be negative, the inside temperature is higher than the outside temperature. The higher inside temperature is caused among others by solar radiation and internal heat sources (people, electric applications). By a negative $\Delta \bar{T}$ the insulation loses some of its benefits, while the benefits of solar reflection remain unchanged. Therefore the conservative assumption is made $\Delta \bar{T} = 0$.

Average solar absorptance: The average solar absorptance depends on the type of roof and its geographical location. For corrugated iron of several years old as used in Box N the solar absorption $\alpha = 0.66$, for a green roof it is approximately $\alpha = 0.73$. Note that these solar absorption rates are only based on estimations (Suehrcke, et al., 2008).

Heat transfer coefficient: The heat gain of a roof depend on the heat loss coefficient to the ambient, h_0 , which in turn depends on the wind speed and the sky temperature. Due to wind and sky radiation h_0 is typically 15-25 W/m^{2}K, with bare metal surfaces in the lower range. Therefore the conservative assumption is made that $h_0 = 20 \, {}^{W}\!/_{m^2 K}$.

Average solar radiation: The average solar radiation can be estimated from solar radiation data of a specific location. The solar radiation varies from summer to winter; in locations close to the equator this variation is smaller. The solar radiation for San Pedro Sula is not exactly known for the days of the research. Therefore the average solar radiation is used, which is 21.9MJ/m^2 or 250 W/m^2. The calculation of the average solar radiation can be read in Appendix B.

For both boxes the total daily heat gain calculated by Equation (5) is:

$$q_N = (2.13 * 24 * 3600) * (0 + (0.66 * 250)/20) = 1508kJ$$

$$q_G = (0.27 * 24 * 3600) * (0 + (0.73 * 250)/20) = 213kJ$$

Compared to the results from paragraph 4.3.2 the results of the normal roof are nearly the same, the measurements are slightly higher than the calculated energy. This is probably caused by incoming sun radiation through the walls.

In contrast with the normal roof the green roof practical measurements are slightly lower than the calculated energy. This indicates that either the insulation value of a green roof is higher or the reflectivity of the plants is higher.

To determine the equivalent of the R-value of a green roof the following equation needs to be solved

$$q_G = U\Delta t\left[\Delta\bar{T} + \frac{\alpha}{h_0}\bar{G}\right] = 176.1\ kJ$$

$$U = \frac{q_G}{\Delta t\left[\Delta\bar{T} + \frac{\alpha}{h_0}\bar{G}\right]} = 0.223$$

$$R = \frac{1}{U} = \frac{1}{0.223} = 4.48\ K * m^2/W$$

This means that the system as build has an equivalent of an R value of 4.48 to a roof. As mentioned before this is only an equivalent, since a green roof helps cooling a building in different ways.

5. Sub conclusion

The results presented in the last few paragraphs point toward some characteristics of the behavior of a green roof in a tropical climate.

First of all, the overall lower inside temperatures of Box G in comparison to Box N confirm that a green roof is an effective cooling technique in a tropical climate. The exact reason for the lower temperatures cannot be proven from the data but some assumptions can be made. The time delay a green roof causes points to a lower thermal conductivity (higher insulation value) or a higher heat capacity of a green roof. Both effects can also take place at the same time.

The overall lower metal sheet temperatures of Box G tell that the heat load on a building with a green roof will be less. This means less heat is pressing on the building and less heat is expected to enter the building. In the best case a green roof can also transport heat out of a building.

The graphical analyses also show that a green roof is of more value in hours of sunshine, because the differences with a normal roof become larger. It can mean that a green roof is a good radiant barrier. A green roof acts probably as a radiant barrier by using radiation energy for biological functions of the plants in so doing preventing heat gain into a building.

Last, the green roofs decrease the temperature fluctuation, regarding range and frequency, of the materials during the day. This can lengthen the life span of the layers beneath the roof, although other characteristics of a green roof can shorten the life span.

After the analysis a mathematical approach was used to quantify the heat prevention of a green roof. The results show that a green roof can prevent heat entering up to 1400 kJ/m^2day compared to a poorly insulated metal sheet roof. This reduction can also be expressed as an equivalent of the R-value. A green roof as studied has an equivalent of an R-value of 4.5 $K * m^2/W$. This is not the exact R-value of a green roof, because it not only works as an insulation technique, but also as a radiant barrier.

6. Financial Analysis

Green roofs provide a large range of benefits from amenity to ecological and technical benefits. In order to stimulate the use of green roofs, they have to be affordable for their possible users. In this chapter an analysis is made of the costs and financial benefits of extensive green roofs. The costs and benefits are expressed per square meter.

6.1 Costs

6.1.1 Initial costs

In Europe and the United Stated the market of green roof systems and green roof installation is more developed than in the local context. With no more than 5 small to medium size, local installed green roofs the market can be called undeveloped. The limited use of green roofs increases the initial costs for materials and installation. The costs of green roofs therefore appear to be much higher than they can actual be in a developed market.

This financial analysis is made for extensive green roofs. The assumption is made that the green roof is considered early in the design stage. Therefore the structural components were already designed to take the additional load and the construction costs would not be substantial different. Thereby literature has noted that due to the lightweight design of extensive green roofs the extra load is minimal and extensive green roofs can also be suitable for existing buildings (O'Keefe, et al., 2008)

Right now two systems are available. The first is constructed of solely local materials made by local workers. The second system is constructed with materials from Green Living Technologies, imported from the United States. The prices as mentioned below are derived from experience with already constructed roofs, but prices still can change due to a developing market.

	Price (dollars/m^2)
Corrugated iron sheet	$7,-
Local system	$40,-
Green living technologies	$150,-

Table 4: Estimated initial costs

6.1.2 Maintenance costs

Maintenance costs are difficult to estimate in this stage. Normally long-term maintenance cost should be low with a self retaining plant selection. However the influence of the tropical climate on the plant growth remains uncertain at this stage.

The maintenance costs are estimated from experience with green roofs in this climate and area. The maintenance costs include weeding and an inspection of the roof system. It is assumed one person needs to perform 8 hours of maintenance per 100 m^2 per month. The hourly salary of a gardener is $1.50 per hour.

The growth of vegetation in a tropical climate needs to be more restricted than stimulated, therefore additional fertilizers are not necessary. Thereby it is assumed that the vegetation survives and replacements or additional plants are not needed.

The yearly costs of maintenance will therefore be $14.40/m^2.

6.2 Benefits

6.2.1 Energy savings

In paragraph 4.3.2 is determined that the daily heat gain of a roof can decrease with 1395.5 kJ/m^2 compared to a poorly insulated metal sheet roof on a day with (partially) sun. Of all days 17% are fully clouded in San Pedro Sula (NASA, 2008). It is assumed that on these days the energy savings are negligible. This means that energy savings takes place on 300 days per year.

To cool this incoming heat an air conditioner is used. Most 5 to 10 year old air conditioners, which are common used in Honduras, have an efficiency of 1:0.75; it means that with 1 kWh of energy 0.75 kWh of energy can be transported out of the room (Wikipedia inc., 2008).

The electricity costs of one kWh of energy are derived from a current electricity bill and are 3 Lempira's. All costs are estimated in dollars and therefore electric energy costs $ 0.15 per kWh.

E/m2	E in kWh	R	E used	Cost	Days	Yearly savings / m^2
1395.5 kJ	0.387 kWh	0.75	0.51 kWh	0.15 $	300	$23.22
32.4 kJ	0.09 kWh	0.75	0.12 kWh	0.15$	300	$5.40

Table 5: Yearly energy savings

6.2.2 Other economical benefits

In several papers in the literature is claimed that a green roof almost double longevity of the layers underneath the green roof. Since those studies mostly are based on flat concrete roofs and the increased longevity of a metal sheet have not been tested thoroughly this is neglected. It is assumed that a normal metal sheet roof has the same life expectancy with and without green roof. The life expectancy of a metal sheet roof in a tropical climate is assumed to be 20 years.

Some other significant benefits as storm water retention, air pollution removal and a cooler microclimate in an urban area are do not only benefit the user but also the municipality, they are hard to quantify and put to a dollar value. Therefore these benefits do not influence the financial analysis.

6.3 Net Present Value

To calculate if the investment costs of a green roof can be paid back by its energy conservation, the net present value (NPV) is used. It is a standard method for using the time value of money to appraise long-term projects. Future costs and benefits are calculated to one base year in this case 2009. The net present value can be calculated through

$$NPV = \sum \frac{R_t}{(1+i)^t}$$

with R_t the net cash flow, i the discount rate and t the time in years. The calculation is made over the expected life span of the green roof, 20 years. The parts taken into account are the initial costs, the yearly maintenance costs and the energy savings.

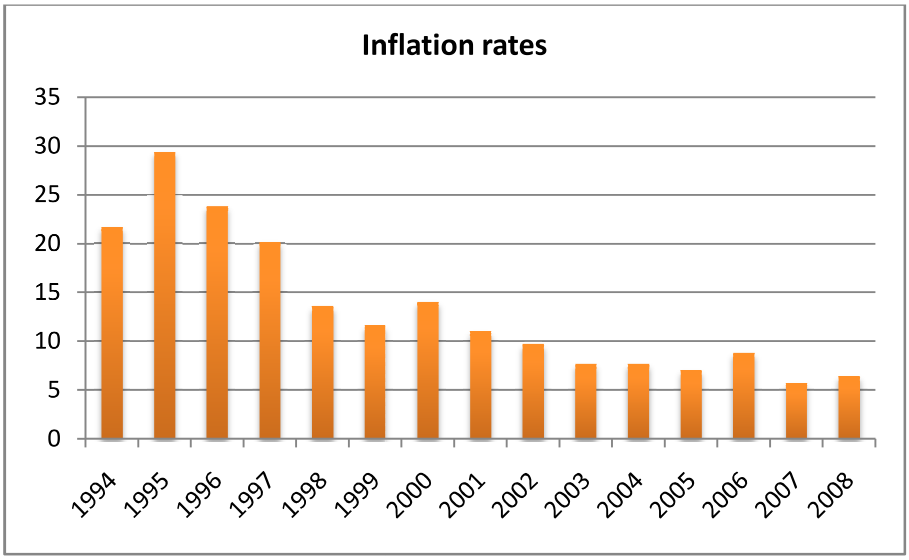

Chart 8: Consumer prices inflation rates (Index Mundi, 2008)

As observed from Chart 8 the inflation rates in Honduras have been in a downward spiraling trend for the past 10 years. The last five years the inflation rates are more or less stable between 5% and 10%. With the ongoing worldwide economical crisis an estimation of the inflation is very difficult to make. The estimation is made that the inflation will be 6% and prices are put in dollars, a more stable currency.

The calculation is based on a single story building with a footprint of 100m^2. The comparison is not only made with a poorly insulated roof. According to Dutch building codes a roof needs to have a minimal R-value of 2.2. Therefore a green roof will also be compared with a medium insulated roof (med ins.) with an R-value of 2.2. Four scenarios are drawn. First a local green roof (local) compared to a poorly insulated (poor ins.) metal sheet roof. Second a local green roof compared to a medium insulated roof with an R-value of 2.2. Third and fourth the green living technologies (GLT) system is compared to a poorly and medium insulated roof.

The daily heat gain of the medium insulated roof is calculated using Equation (5) and the energy savings are calculated through comparison with the green roof.

		Initial costs	Maintenance cost per year	Savings in energy costs	Net present value
Scenario 1	Local – poor ins.	$ 4000,-	$ 144,-	$ 2322,-	$ 20981
Scenario 2	Local – med ins.	$ 4000,-	$ 144,-	$ 540,-	$ 542
Scenario 3	GLT – poor ins.	$ 15000,-	$ 144,-	$ 2322,-	$ 9981
Scenario 4	GLT – med ins.	$ 15000,-	$ 144,-	$ 540,-	$ -10458

Table 6: Net present value of 4 scenarios

A negative net present value means that the initial costs cannot be earned back in the life span of the roof. As Table 6 shows, in three of the four scenarios a green roof makes more benefits than the initial costs. It has to be noted that minimal insulation value of a green roof according to Dutch building codes is 2.2, Honduran building codes do not oblige a certain minimal insulation value. Scenario 3 and 4 are more likely to occur.

The financial analysis shows us that a green roof can be profitable in a tropical climate as a passive heat prevention technique for buildings. Even though it must be said that placing bulk insulation in a building is in most cases a cheaper solution. With more development of the local system it can be used more confidently. The development of the local market can lower the prices in the future, what would make a green roof even more profitable in a tropical climate.

7. Sub Conclusion

The analysis of the financial aspects of a green roof show that with a life time of 20 years a green roof can be profitable compared to a low or medium insulated roof. The analysis also indicated that the market in Honduras is at the present time is not yet developed and therefore the market prices are not set exactly. The long term effects of a tropical climate on its life time and maintenance cost are in this stage still uncertain and have to be quoted exactly after more experience.

Despite the benefits of energy conservation a green roofs has numerous other benefits that could not be researched practically in this time span. These benefits include: storm water management, mitigation of the urban heat island effect, increased durability of roofing membranes and mitigation of noise and air pollution, as well as a more aesthetically pleasing environment in which to work and live. To qualify and quantify these benefits more research is necessary and a more complete overview of the benefits of a green roof in a tropical climate can be given.

8. Conclusion

A theoretical study together with experiences was used to discover the benefits and difficulties of green roofs in a tropical climate. Green roofs can be constructed because of their ecological character but either or because of their aesthetical design. A distinction between types of green roofs can be roughly made by their thickness of the soil layer. Intensive green roofs have a thicker soil layer than extensive green roofs.

In the theory numerous benefits of green roof were discussed. The environmental benefits of green roofs include storm water management, energy conservation, mitigation of the urban heat island effect, increased longevity of roofing membranes, and mitigation of noise and air pollution, as well as a more aesthetically pleasing environment in which to work and live. An important aspect of green roofs is their positive influence on the inner climate of a building and their prevention of heat radiation to the surrounding area. They cool a building by providing shadow over the roof, a main factor in passive cooling. The plants use a substantial part of the solar radiation for their biological functions, in so doing working as a radiant barrier. Furthermore they increase the insulation value and heat capacity of a roof.

The practical part of the study confirms the results found in the literature. Their overall lower temperatures of the underlying surfaces showed that they reduce the heat load on a building. Their high effectiveness on days with a lot of sun hours prove that they act as a radiant barrier. Last a green roof reduces the temperature fluctuations of the underlying surface, which increases the durability of the material.

With a mathematical analysis the heat prevention of a green roof was quantified. The results show that a green roof can prevent heat entering up to 1400 kJ/m^2day compared to a poorly insulated metal sheet roof. This reduction can also be expressed as an equivalent of the R-value. A green roof as studied has an equivalent of an R-value of 4.5 $K * m^2/W$. This is not the exact R-value of a green roof, because it not only works as an insulation technique, but also as a radiant barrier.

In the performed financial analysis, the costs and benefits of green roofs were compared in four scenarios. First, a local developed system was compared with a poorly and a medium insulated roof. Second, a pre-fabricated system from Green Living Technologies was compared with a poorly and a medium insulated roof. The results show that a green roof can be profitable in a tropical climate in a life span of 20 years. The analysis also showed that the market in Honduras is not developed yet, which can cause a price variation in the next decades.

Appendixes

A. Definition of thermal resistance (R-value)

For the following development, a clear understanding of the definition of the thermal resistance value (R-value) is important. The steady state heat flow through a certain surface (heat flux) can be expressed as $\frac{Q}{A}$. With a fixed temperature difference ΔT through a wall or roof and the overall heat transfer coefficient is $U = \frac{1}{R}$ this can be described as

$$q = \frac{Q}{A} = U\Delta T = \frac{\Delta T}{R} \tag{6}$$

The problem with the equation as mentioned above that it does not apply for illuminated surfaces. To make the equation applicable to a sun illuminated surface the sol-air temperature difference is needed.

$$T_{sol-air} = T_a + \left(\frac{\alpha G}{h_0}\right) \tag{7}$$

where T_a is the ambient air temperature, α is the surface solar absorption, G the solar irradiance and h_0 the roof to ambient heat transfer coefficient. Using the sol-air temperature q can be written as

$$q^* = \frac{Q^*}{A} = U\Delta T_{sol-air} = \frac{\Delta T_{sol-air}}{R} \tag{8}$$

Dividing Equation (6)by Equation (8)gives

$$\frac{q^*}{q} = \frac{Q^*}{Q} = \frac{\Delta T_{sol-air}}{\Delta T} = F$$

where F is the factor of increase in heat flow due to the solar illumination (in case of heat loss from the building, the solar heating may decrease the heat loss). The latter factor allows one to express the roof heat flow, which includes the effect of solar illumination as

$$q^* = \frac{\Delta T_{sol-air}}{R} = \frac{\Delta T F}{R} = \frac{\Delta T}{R^*}$$

B. Calculation of solar radiation

Sunlight, in the broad sense, is the total spectrum of electromagnetic radiation given off by the sun. When the direct radiation is not blocked by clouds, it is experienced as sunshine, a combination of bright light and heat. Radiant heat directly produced by the radiation of the sun is different from the increase in atmospheric temperature due to the radiative heating of the atmosphere by the sun's radiation.

Sunlight is usually thought of in terms of power per unit area with the typical unit W/m^2. The amount of incoming solar electromagnetic radiation per unit area, measured on the outer surface of earth's atmosphere in a plane perpendicular to the rays is called the solar constant. The solar constant includes all types of solar radiation, not just the visible light. It is measured by satellite to be roughly 1367 W/m^2). The value fluctuates during a year due to the earth's varying distance from the sun. These values correspond to high noon with the sun directly overhead (as would occur at the equator).

The energy from sunlight in Honduras during October and November can be obtained from this number and a little geometry. The total energy is:

$$J = \left({}^{W}\!/_{m^{-2}}\right) * \ A(m^2) * t(s)$$

The sun isn't always directly overhead; it moves East-West throughout the course of a day and North-South throughout the course of a year. It is known that the sun mover 23.5^{o} above and below the equator over the course of a year. It is on the equator every 21st of March and 21st of September. We estimate the sun's position north of the equator by:

$$\theta = 23.5° \sin(2\{\Delta T/365.25\})$$

In which ΔT is the number of days counted from the vernal equinox (21st of April). Then we estimate the solar constant for any particular day by calculating:

$$\sigma = \left(1367\, {}^{W}\!/_{m^{-2}}\right) \cos(L - \theta)$$

In which $L = 15°$ is the latitude of San Pedro Sula.

The daily variation: Let the sun be at altitude A (angle above the eastern horizon) at a given time t during the day. Then at time $t + \Delta t$ the altitude will have increased to $A + \Delta A$. The differential time is related to the differential altitude by

$$\Delta t = \left(\frac{12}{\pi}\right) \Delta A\ hr$$

Since the sun travels through π radians (180°) in 12 hours. So the energy collected during a day on a surface of 1m^2 is:

$$\Delta E = \sigma \sin A \, dt$$

$$\Delta E = \sigma \sin A \left(\frac{12 * 3600}{\pi}\right) dA$$

Which can be integrated from A = 0 to A = π to get:

$$E = \sigma \left(\frac{12 * 3600}{\pi}\right) * -\cos A$$

If we now fill in all the values that belong to the case:

$$\Delta T = 183d$$
$$L = 15°$$
$$\theta = 23.5° \sin\left(2\left\{\frac{\Delta T}{365.25}\right\}\right) = 0.4°$$

$$\sigma = \left(1367 \, {}^{W}\!/_{m^2}\right) * \left(\frac{\pi}{2}\right) \cos(L - \theta) = 1967 \, {}^{W}\!/_{m^2}$$

$$E = \sigma \left(\frac{12 * 3600}{\pi}\right) - \cos A$$

$$E = 27.0 * 10^6 \, J$$

The sun radiation is also measured by satellites of the "National Aeronautics and Space Administration (NASA), which can be requested in the atmospheric science data center. In this database the sun radiation is measured to be 6.10 kWh/m^2/day on the geographical location of San Pedro Sula (15° 30' 0" North, 88° 2' 0" West) (NASA, 2008).

$$1 \, kWh = 3.6 * 10^6 J$$

$$5.81 \, kWh = 21.9 * 10^6 J$$

Both values are in the same order, the assumption is made that the sun radiation in San Pedro Sula on an average day in October or November is $21.9 * 10^6 J$.

C. Steady state temperature of a surface

The temperature of a roof surface depends on the environmental conditions (solar radiation, ambient temperature, wind velocity and sky temperature), the optical properties of the roof surface (solar absorptance and thermal emittance) and the underside insulation. For a surface with perfect insulation at the underside and steady state the absorbed solar radiation must equal the heat loss due to convection with the air and thermal radiation heat exchange with the sky.

$$\begin{aligned} \alpha G &= h_c(T - T_a) + h_r(T - T_{sky}) \\ &= h_0(T - T_a) \end{aligned} \tag{9}$$

with h_c is convective heat transfer coefficient between roof and ambient air, h_r is radiative heat transfer coefficient between roof surface and sky and h_0 is the outside total heat transfer coefficient between roof and ambient air. Solving Equation (9) for the surface temperature gives

$$\begin{aligned} T &= \frac{\alpha G + h_c T_a + h_r T_{sky}}{h_c + h_r} \\ T &= T_a + \frac{\alpha G}{h_0} \end{aligned} \tag{10}$$

D. Derivation of the steady state roof heat flow equation

For steady state, the sum of the energy flowing in and out of the roof surface due to temperature differences and solar radiation absorption must equal zero. Moreover, the heat flow to the inside must equal the net heat flow from between roof and ambient and the solar radiation absorbed on the roof surface. Using the previously defined symbols, the following energy balances for the roof surface and heat flows can be formulated

$$h_0(T - T_a) + h_i(T_i - T) + \alpha G = 0 \tag{11}$$

$$q^* = h_i(T - T_i) = h_0(T_a - T) + \alpha G \tag{12}$$

Solving and adding Equation (11)and Equation(12) results in:

$$\begin{aligned} T_a - T &= \frac{q^* - \alpha G}{h_0} \\ T - T_i &= \frac{q^*}{h_i} \\ T_a - T_i &= q^*\left(\frac{1}{h_0} + \frac{1}{h_i}\right) - \frac{\alpha G}{h_0} = \frac{q^*}{U} - \frac{\alpha G}{h_0} \end{aligned} \tag{13}$$

where $\frac{1}{U} = \frac{1}{h_0} + \frac{1}{h_i}$ is the overall heat transfer resistance between the outside and inside. Now solving the above equation for q^* gives Equation (4).

E. Graphs of all measurement days

In this appendix the graphs with average temperatures are of all days are shown. The weather conditions of all days are shown in Table 7.

Day	Sunshine	Clouds	Wind	Rain
06-Oct	High	Low	Low	None
08-Oct	Medium	Medium	Low	None
09-Oct	Low	Medium	Medium	None
10-Oct	High	Low	Low	None
13-Oct	High	Medium	Medium	Low
14-Oct	Low	High	Medium	Low
05-Nov	Medium	Medium	High	None
12-Nov	Medium	Medium	Medium	None
13-Nov	Medium	Low	Low	None
14-Nov	High	Medium	High	None
15-Nov	Low	High	Medium	High

Table 7: Logbook

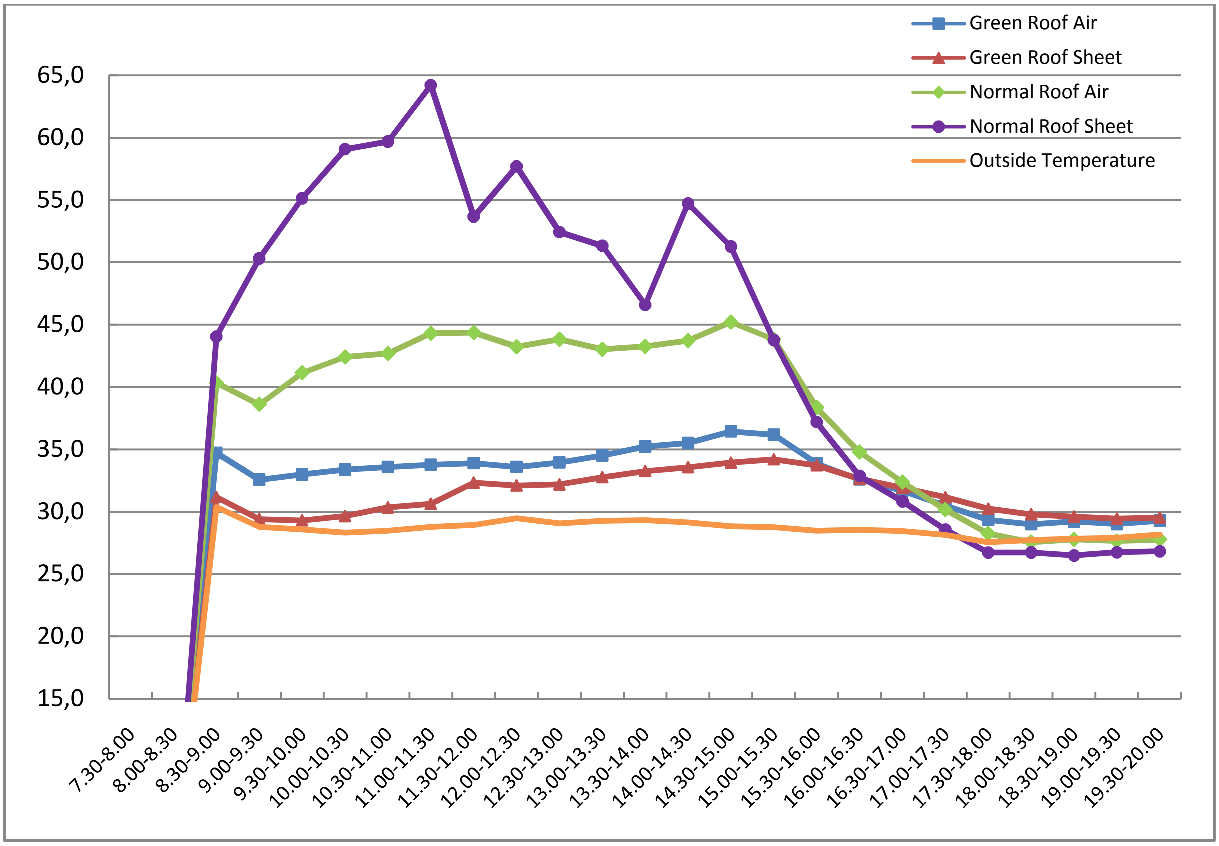

Chart 9: Average temperature 6-Oct

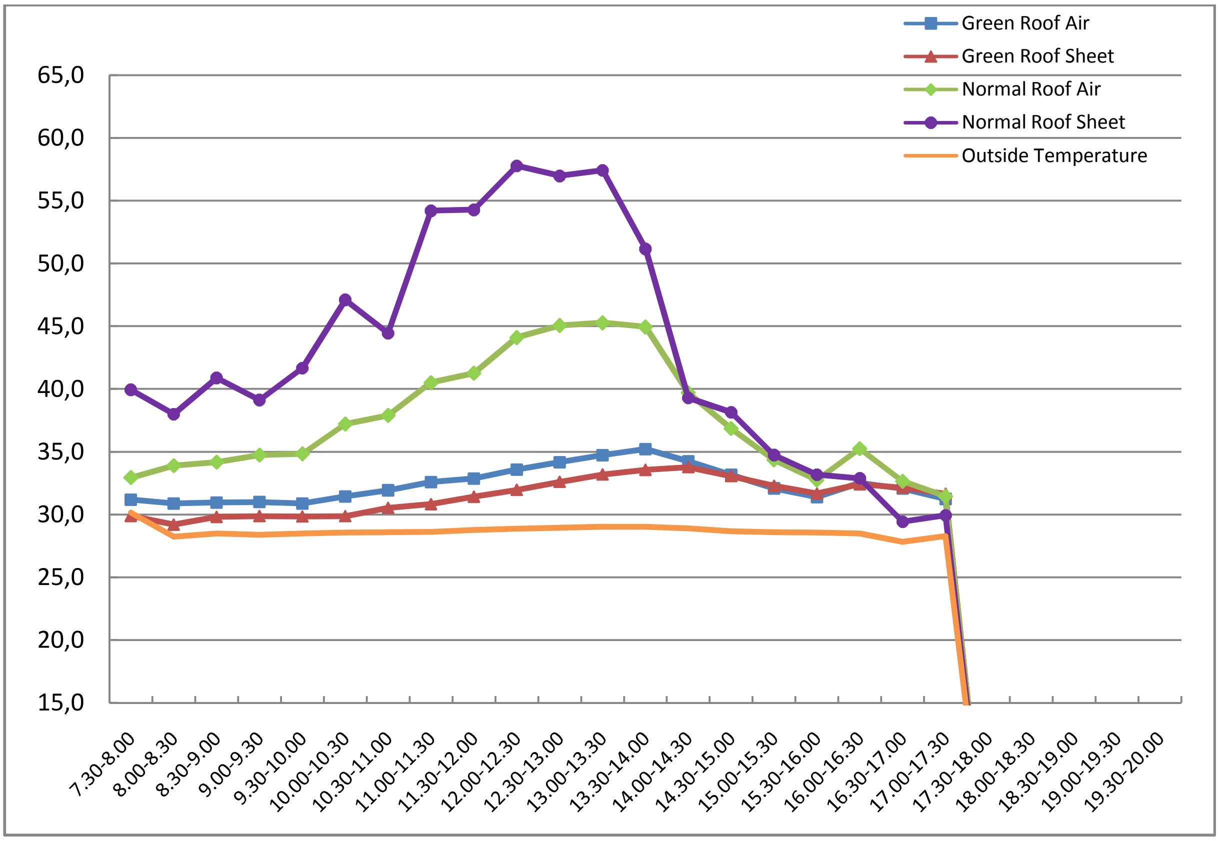

Chart 10: Average temperature 8-Oct

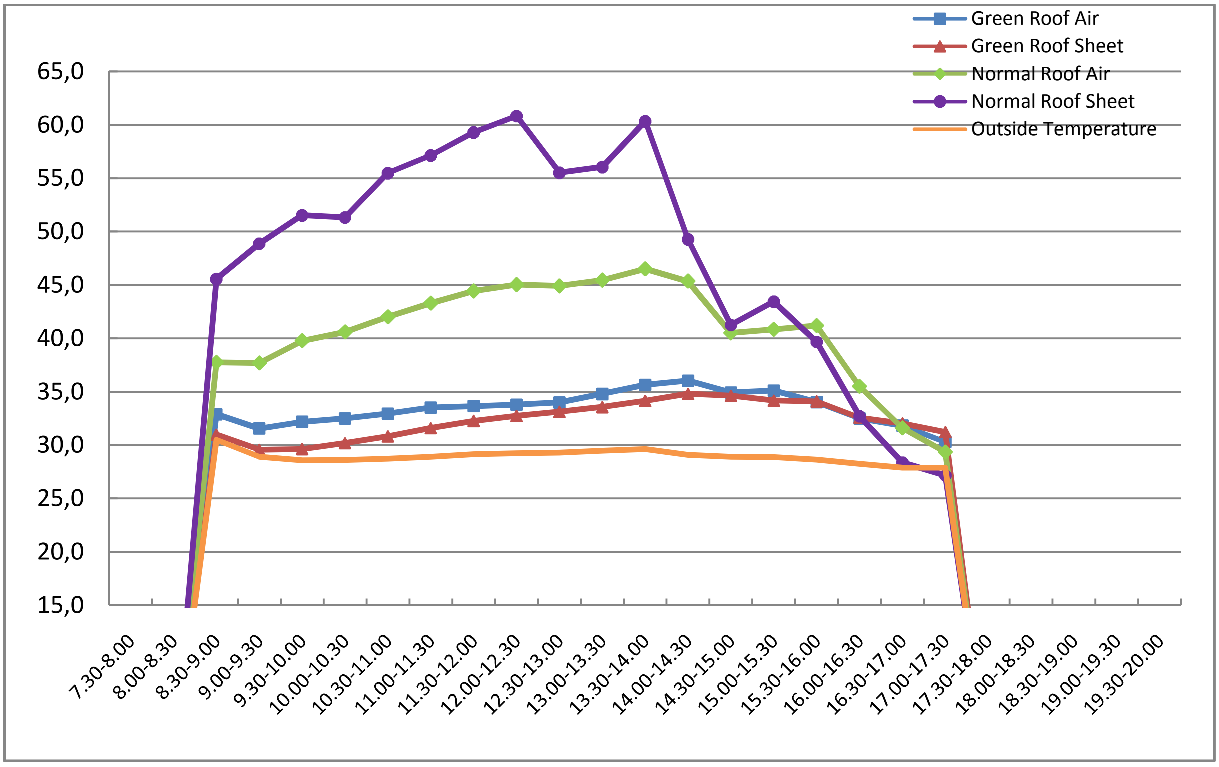

Chart 11: Average temperature 09-Oct

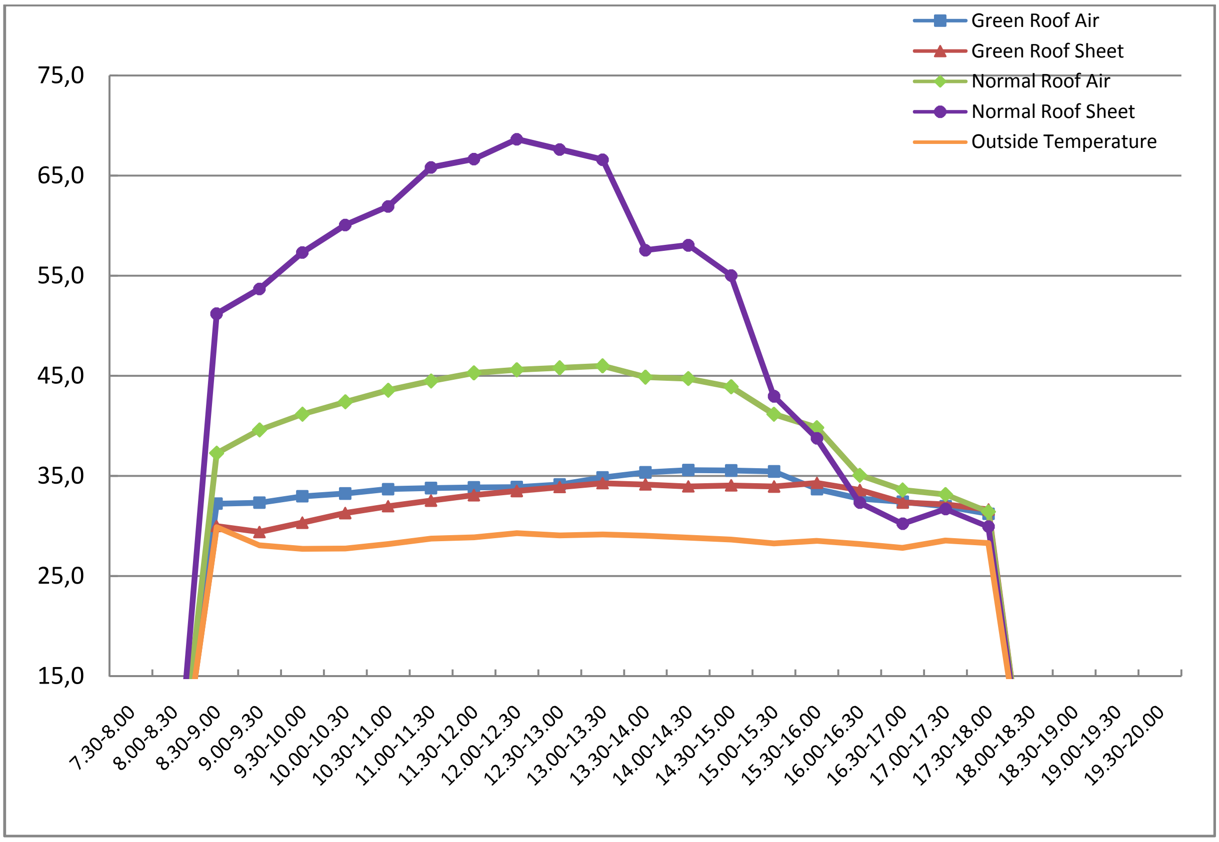

Chart 12: Average temperature 10-Oct

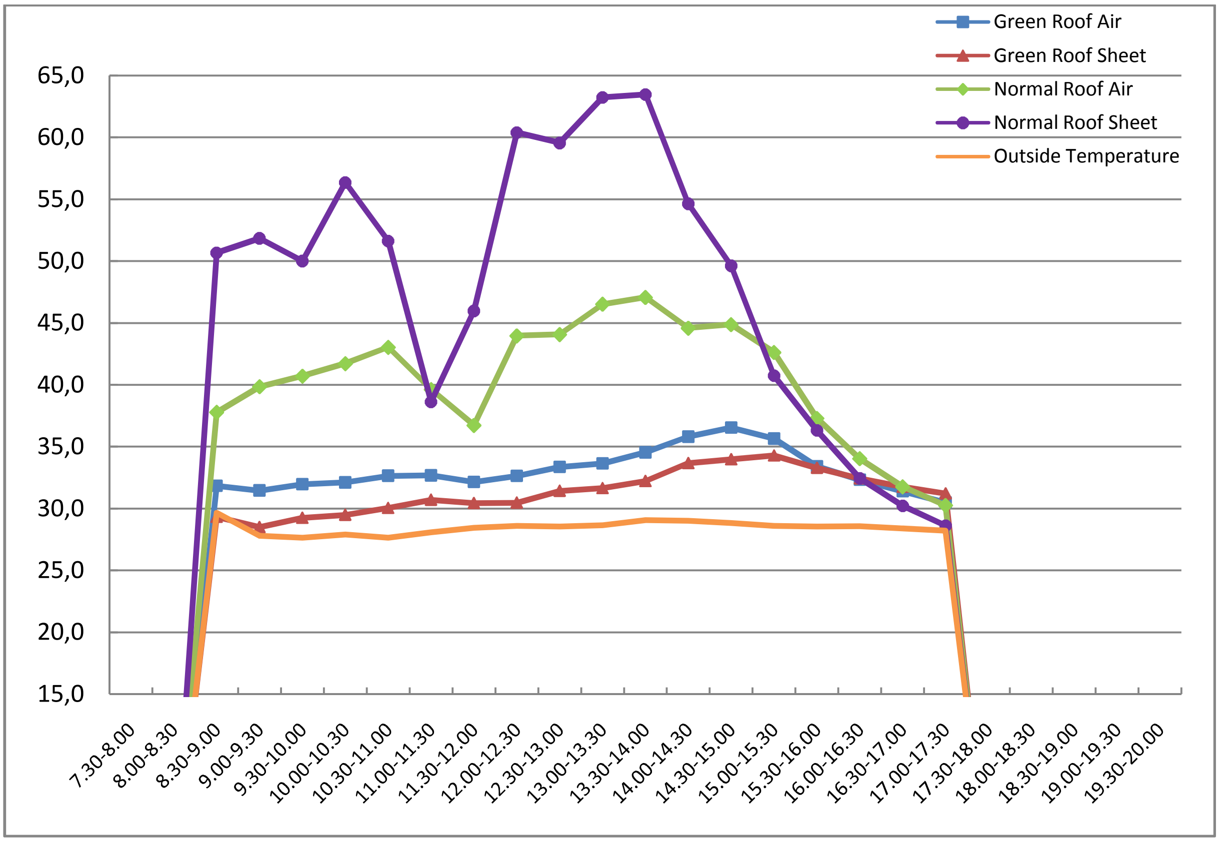

Chart 13: Average temperature 13-Oct

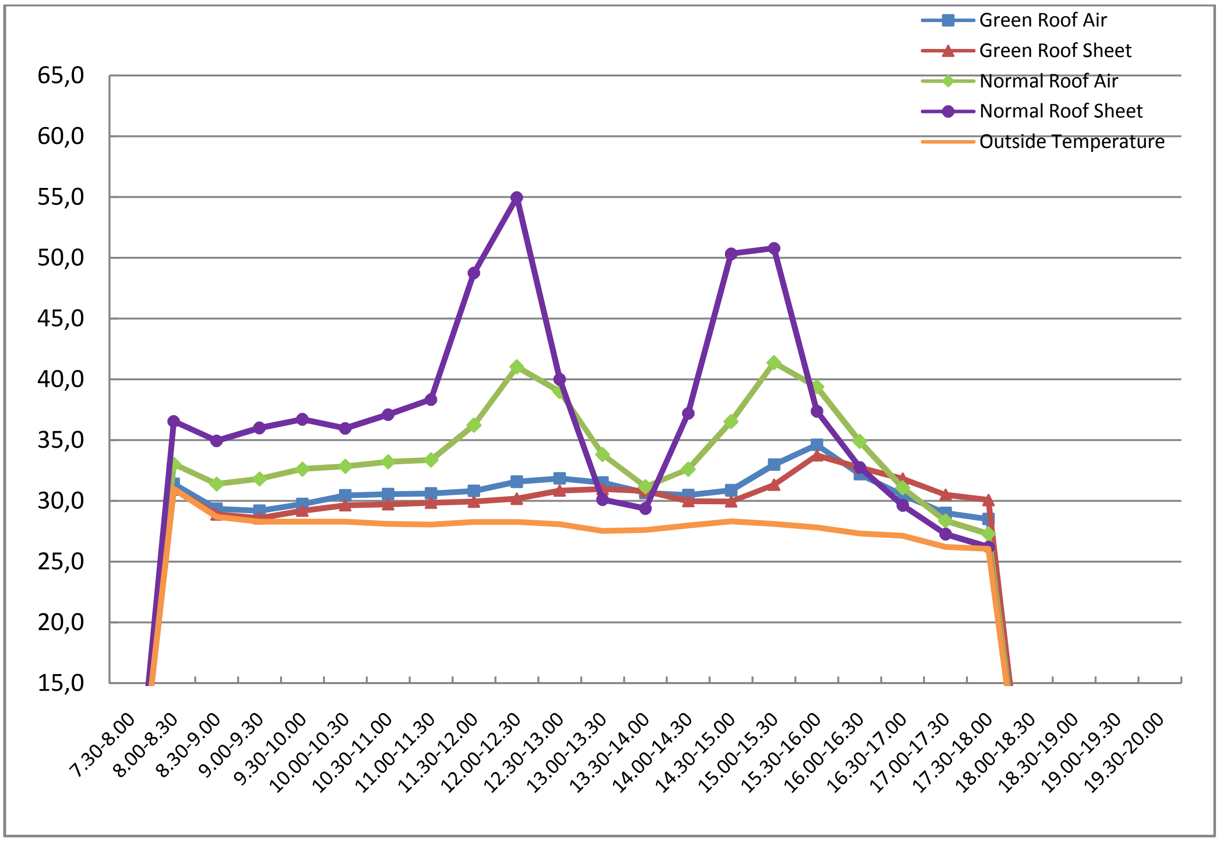

Chart 14: Average temperature 14-Oct

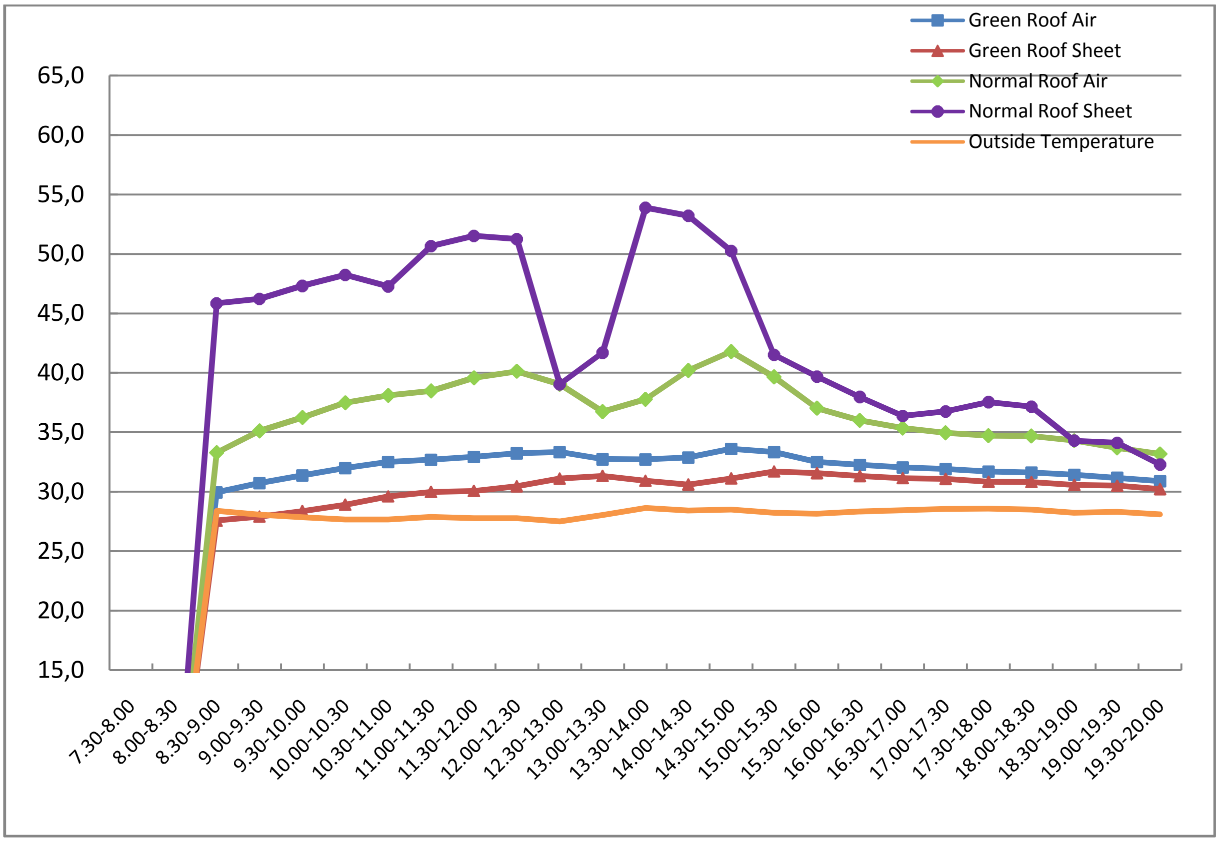

Chart 15: Average temperature 05-Nov

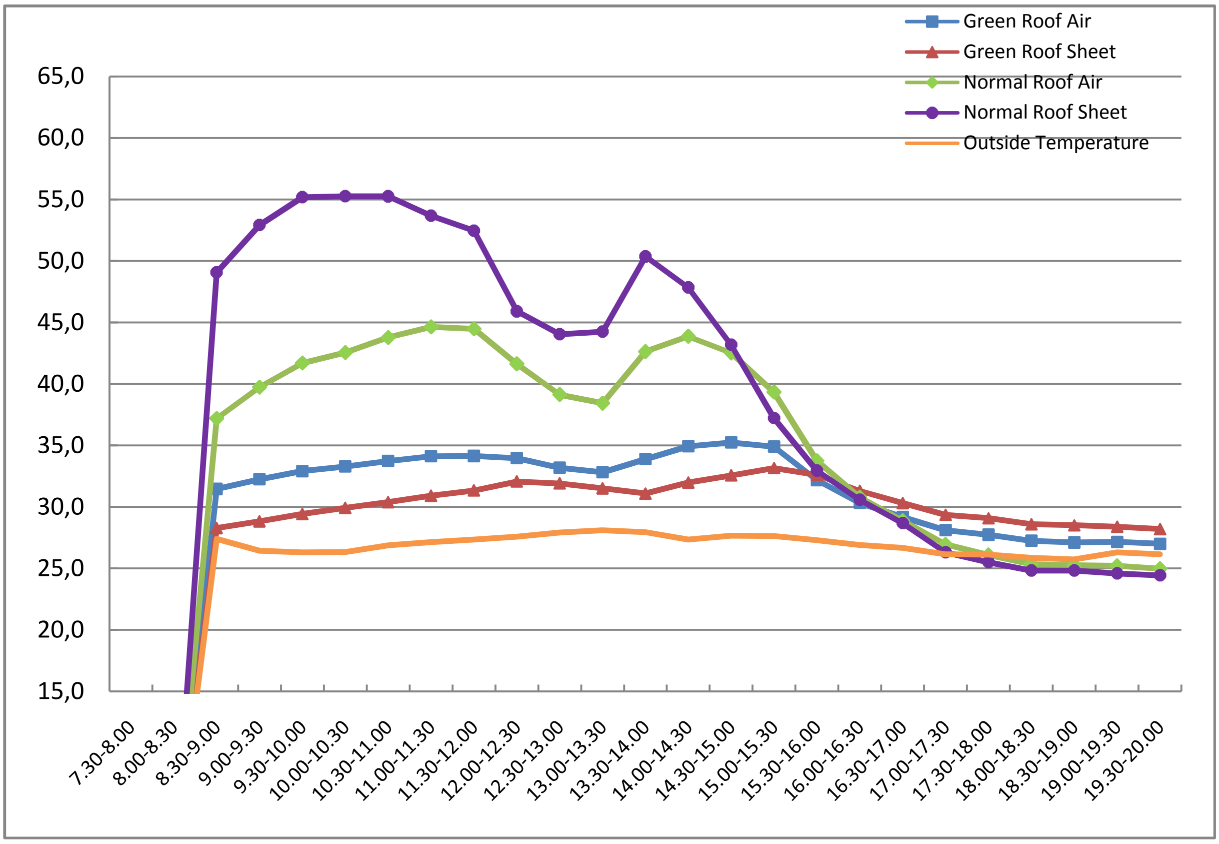

Chart 16: Average temperature 12-Nov

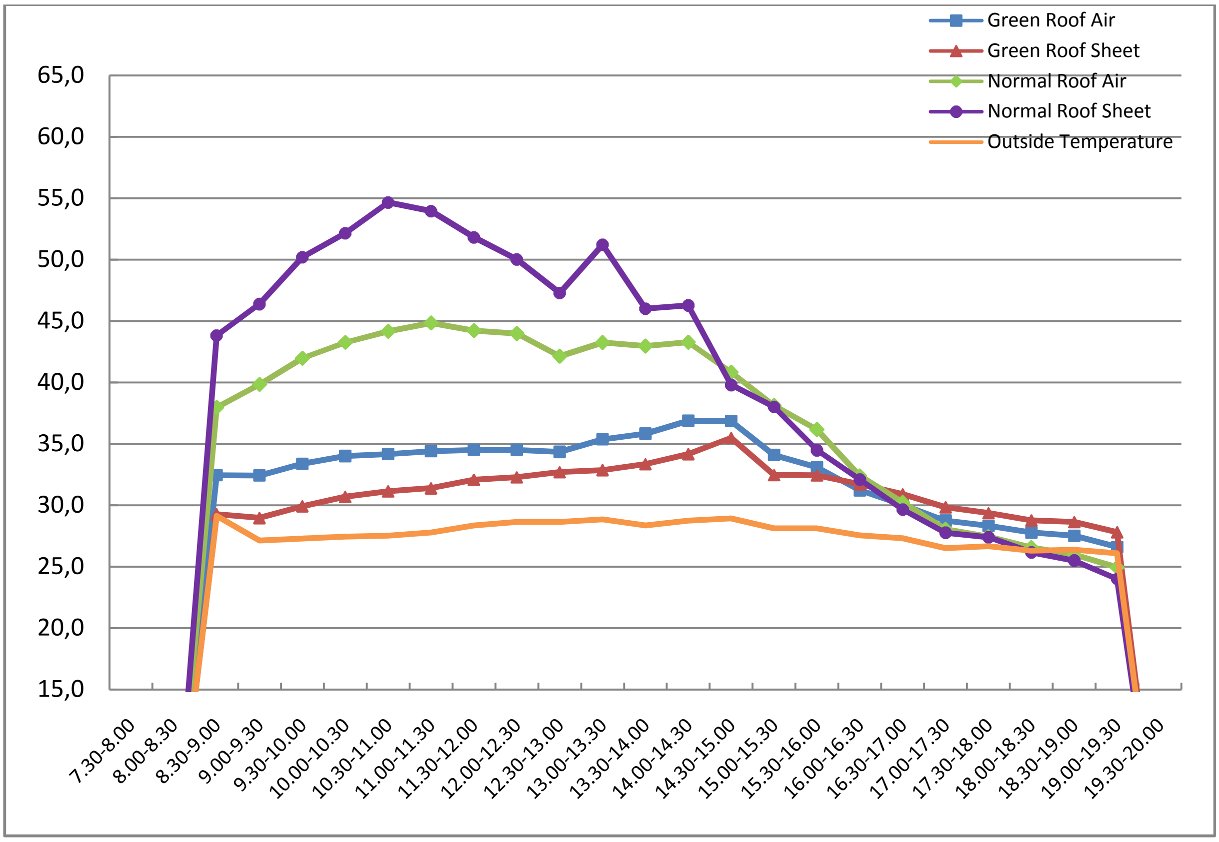

Chart 17: Average temperature 13-Nov

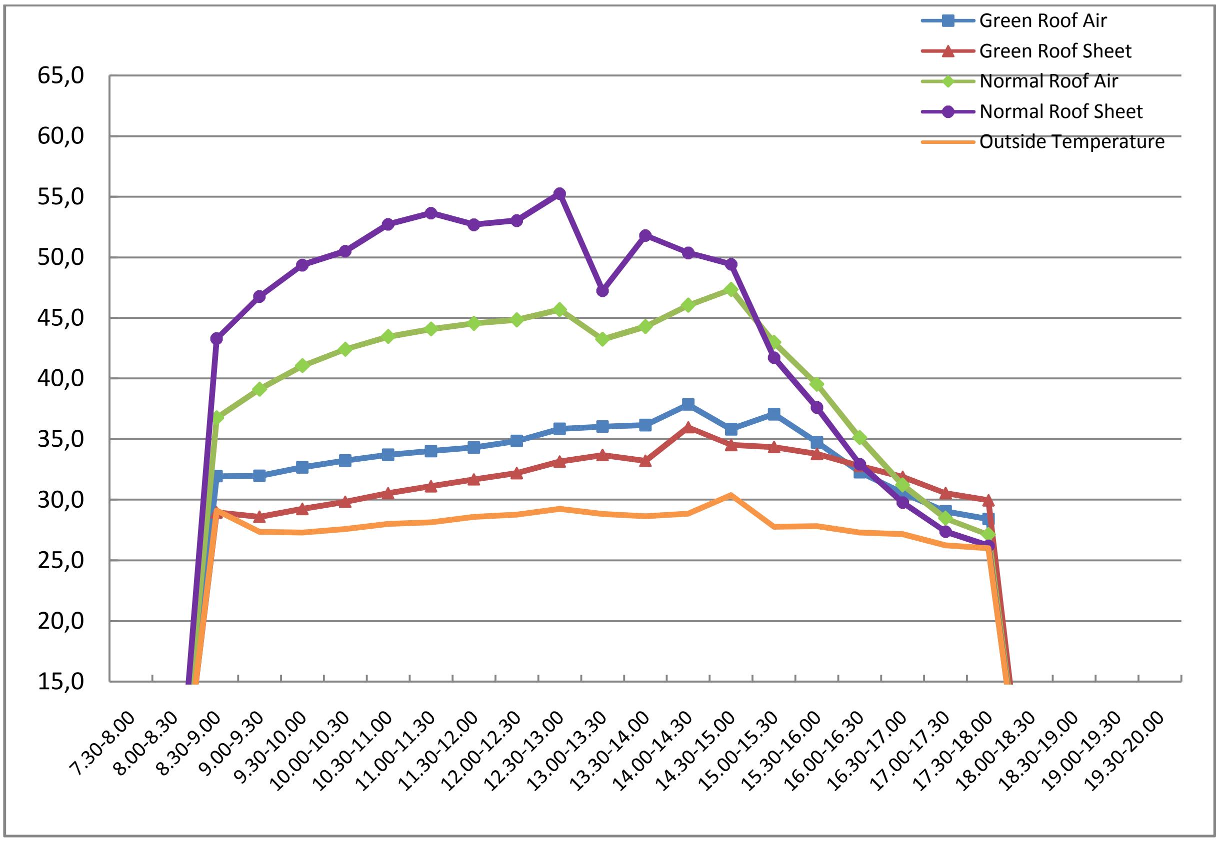

Chart 18: Average temperature 14-Nov

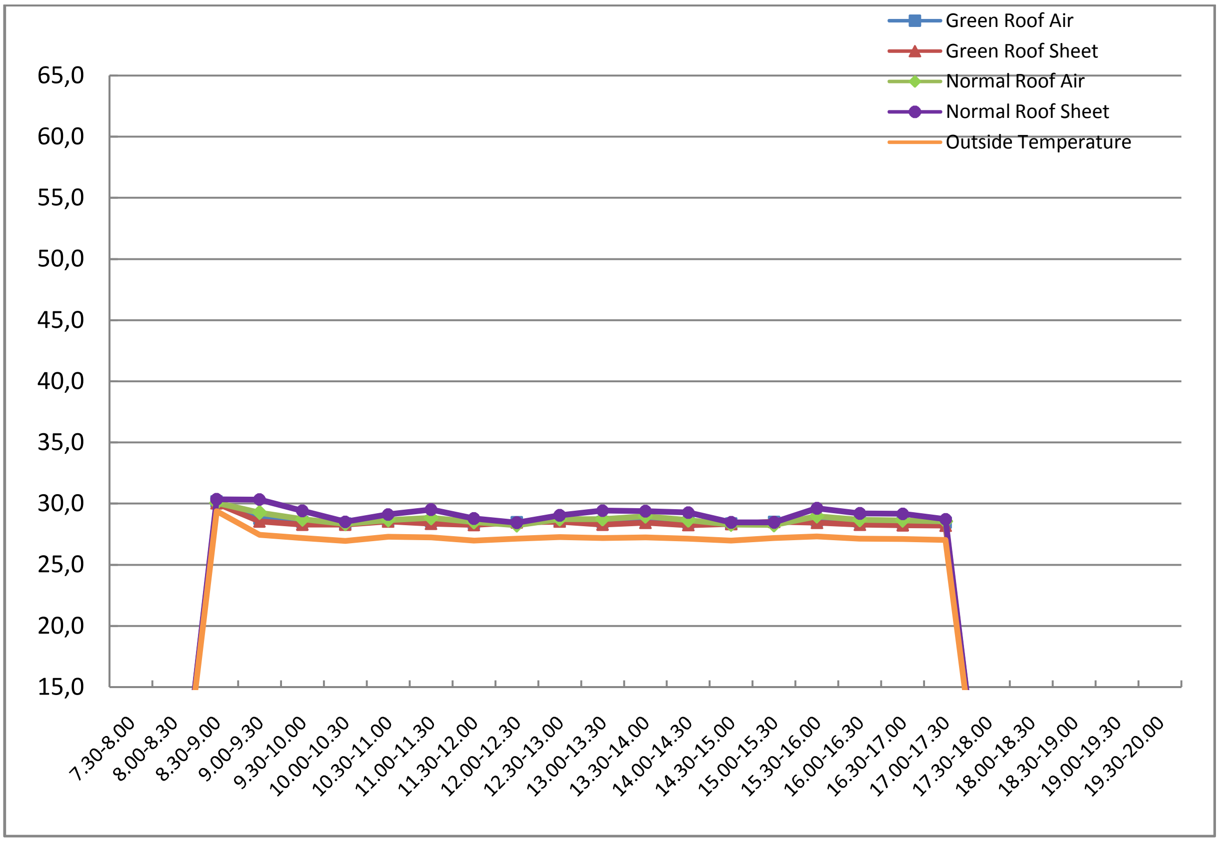

Chart 19: Average temperature 15-Nov

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