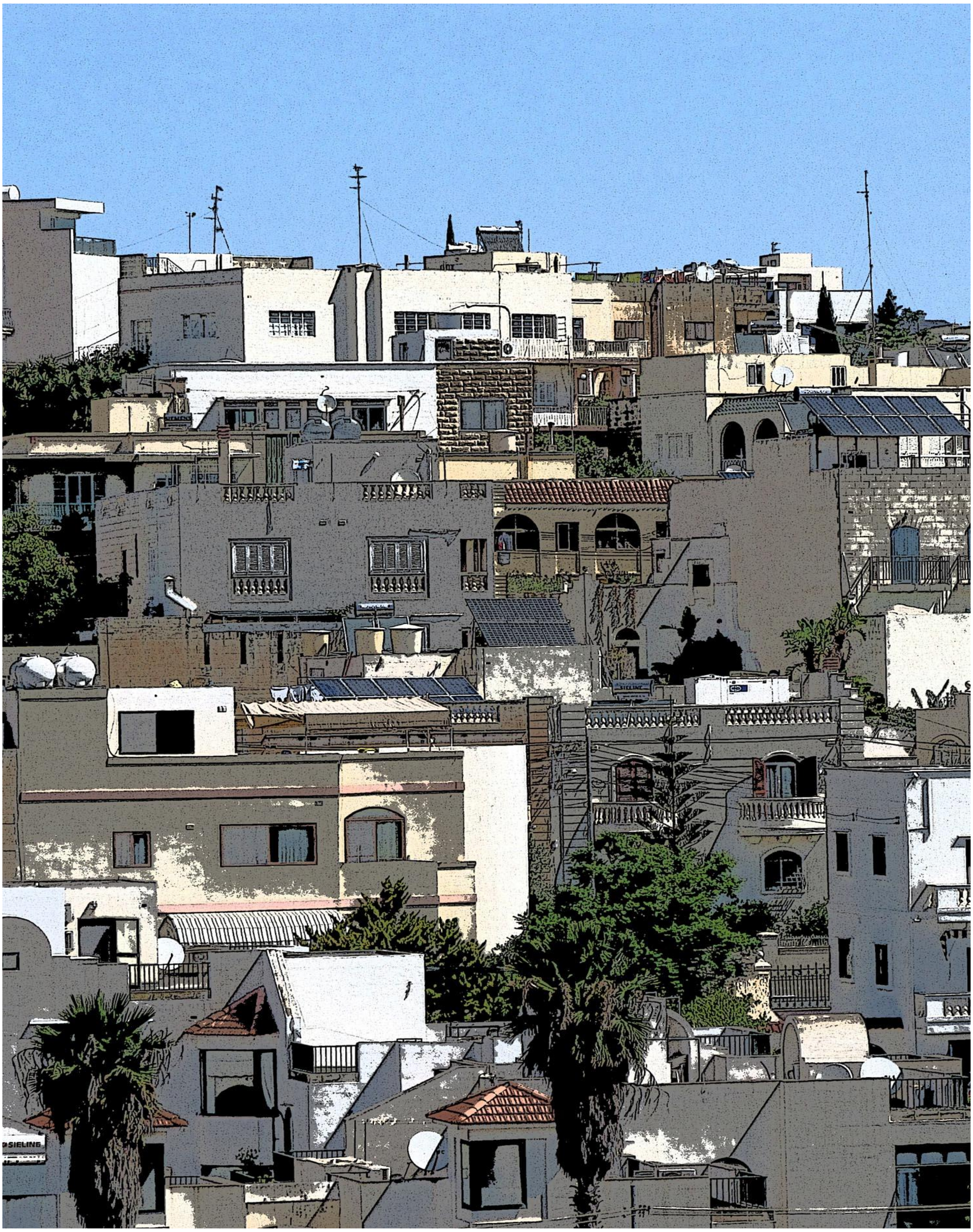

LifeMedGreenRoof Project
Green Roof Thermal Performance

Life12 ENV/MT/000732

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Executive Summary

It has been shown that green roofs can moderate extremes of temperature and thereby can improve a building's overall energy performance. Much research has been carried out on the performance of green roofs in the northern hemisphere for instance in Germany and USA, where attention has predominantly been placed on preventing heat loss through the roof in the heating or winter season. However, very little has been studied on the performance of such roofs in the Mediterranean region particularly in the reduction of heat gains in the cooling period of summer. The LifeMedGreeRoof Project has looked at the potential benefits that green roofs could bring to the Mediterranean region and to Malta in particular. It has also considered briefly any barriers that may hinder the implementation of green roofs.

One of the main aims of the Project has been to investigate the effectiveness of green roofs on buildings to insulate the occupied spaces beneath. Heat sensors embedded both within the layers of a green roof and an adjacent, conventional, slab roof have quantified the conductive heat transfer through both. This data has provided information on how effective the installation of green roofs could be in increasing the energy efficiency of Maltese buildings.

The investigation has been carried out in three main phases. The first phase consisted of a desk top revision of previous investigations into the thermal performance of green roofs both worldwide and more specifically focused on the Mediterranean region. The second phase set up a number of 1m² test trays that examined the effects of such parameters as depth of planting media, and humidity on the thermal performance of a green roof. It also examined the influence that plants may have on the cooling performance of green roofs. In the third phase, the thermal performance of a green roof installed above the Faculty for the Built Environment at the University of Malta was investigated. Comparative readings recorded heat gains experienced beneath the green roof and the conventional roof.

1 Introduction

" There's one issue that will define the contours of this century more dramatically than any other, and that is the urgent threat of a changing climate."

Barack Obama, President of the United States of America,

UN Climate Change Summit, September 23, 2014 (USA, 2014).

There is an increasing realisation that the greatest threat to the continuing existence of human kind on earth is that emanating from the effects of Climate Change. Predictions foretell of increasing incidents of natural disasters such as spreading desertification, violent storms and rising sea levels. The cause of this is the insidious increase in the earth's atmospheric temperature, otherwise referred to as Global Warming and this is thought to be largely due to the continuing burning of fossil fuels to produce energy (Whitefield, 2015). This threat to our survival is now regarded as real and many countries and alliances are putting into place strategies that will hopefully reduce our dependence on energy produced from the use of fossil fuels thus contributing to the stabilisation of the earth's atmospheric temperature.
For instance, Europe has in place 'The Energy Performance of Buildings Directive' (European Parliament, 2010) which requires all new buildings to be Nearly Zero-Energy Buildings (NZEB) by the end of 2020 and all new public buildings to be Nearly Zero-Energy by 2018 (Building Regulation Office, 2015). This is a recognition of the fact that buildings in particular are significant users of energy.

"The building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy. Given the massive growth in new construction in economies in transition, and the inefficiencies of existing building stock worldwide, if nothing is done, greenhouse gas emissions from buildings will more than double in the next 20 years."

Sylvie Lemmet, Director Division of Technology, Industry and Economics UNEP (Buildings and Climate Change Summary for Decision-Makers)

It is therefore evident that the building sector must address the issue of energy use and reduce greenhouse gas emissions from buildings. This must be a cornerstone of every national climate change strategy. It is with this aim in view, that the European Commission is driving forward its mission to increase the development of Nearly Zero Energy Buildings (NZEB) including within the islands of Malta.
Nearly Zero-Energy Buildings are defined as those that have very high energy performance. Ideally they should take advantage of passive means of providing lighting, ventilation and space heating or cooling rather than depend on mechanical means. Ideally, this renewable energy should be produced within the site itself or as near as is practically possible.

European Union countries have been directed to draw up national plans that describe how the general aims will be achieved within that particular country in order to increase the number of nearly zero-energy buildings. The Maltese National Nearly Zero-Energy Buildings (NZEB) Plan was published in August 2015 (Building Regulation Office, 2015). It outlines the particular situation existing on the islands. The Plan makes the point that Malta has a limited range of renewable resources available. The most obvious source for buildings on an island famed for its sunshine is solar-based and mostly Photo Voltaic (PV) and Thermal. However, the Plan makes the point that even solar-based renewables have limiting factors such as shading from surrounding buildings and often lack of easy access to roof spaces. In many countries, the construction of communal PV 'farms' have helped to overcome these constraints. But in Malta, the scarcity of land inhibits the installation of PV 'farms'.

As a response to these constraints found in Malta, the NZEB Plan focuses on the implementation of a two-pronged approach. Firstly, attention will be paid to building regulations that will concentrate on energy efficient materials and building services. The second initiative would be the promotion of the use of solar-based Renewable Energy Sources (RES) which would be applied whenever possible. In addition to regulations that are to be applied to new-build, the Maltese NZEB Plan also contains policies and measures to encourage retrofitted, existing buildings to become Near Zero Emission Buildings. The numerical indicator of primary energy use is expressed as kWh/m^2per year. The two strategies to be applied to buildings in Malta would result in a mean figure of $75kWh/m^2$per year for domestic dwellings and $220kWh/m^2$per year for other buildings (Building Regulation Office, 2015)

A European Commission progress report from 2013 (J. Groezinger, 2014) found that EU countries had to significantly step up their efforts to take advantage of the opportunities presented by nearly zero-energy buildings. As will be discussed later within this study, it is possible that green roofs could make a significant contribution to the goal of creating NZEBs whether new build or retrofitted.

2 Revision of Green Roof Development and Research (Phase 1).

2.1 Early Development of Green Roof Technology – Germany

Modern day 'Green roof technology' can be said to have begun in the early 1970's in Germany when the first green roof systems were developed and commercially sold on a relatively large scale. The initial research carried out was in response to the occurrence of serious storm-water issues that made many German cities think about innovative solutions involving 'green technology'. German research developed into a modern green roof technology with high performance, lightweight materials utilized to grow hardy vegetation even on roofs that were not originally designed to take heavy loads. In the 1980's modern green roof technology was common knowledge in Germany while it was practically unknown in any other country in the world. The German systems offered a proven technology that consisted of reliable irrigation systems and reassuringly for the owner, a protective layering that prevented ingress of roots and moisture.

At this time, that is in the late 1980's, it became increasingly acknowledged that green roofs were valuable, not only in alleviating local flooding but also in the restoration of wildlife habitats lost to urban sprawl and also in terms of their energy saving potential at a time when oil prices were fluctuating wildly. The German government between 1983 and 1996 launched incentive programmes to promote green roofs particularly in city centres. This support reduced the cost of green roofs considerably (N. Dunnett, 2008) . It is estimated that today, 10% of all German roofs are green, with about 10,000,000m² of new green roofs being constructed each year. (Wikipedia, 2016)

The German Landscape Research, Development and Construction Society (FLL) has issued standards for green roof technology. Their 'Guideline for the Planning, Execution and Upkeep of Green-Roof Sites' (FLL-guidelines) reflects the latest developments in German acknowledged state-of-the-art technology. These guidelines have been adopted and modified by many countries both in Europe and in America (Philippi, 2002). Standards applicable to Malta have been drafted through a collaboration between the Faculty for the Built Environment, University of Malta and the Malta Competition and Consumer Affairs Authority (MCCAA) as part of the LifeMedGreenRoof Project (LifeMedGreenRoof, 2016). The popularity of green roofs is increasing and they have become the subject of much scientific research. A number of European countries have very active associations promoting green roofs including Germany, Switzerland, the Netherlands, Norway Italy, Austria, Hungary, Sweden, the UK and Greece. These individual associations have come together to form a European Federation to promote research, to disseminate information and encourage the installation of green roofs. (Efb., 2016).

2.2 Review of Non-Mediterranean Scientific Research into Green Roof Thermal Performance

Austria

Although little investigation has been carried out on the performance of green roofs in the Mediterranean region, in other parts of the world, considerable research has been undertaken. Research at the University of Natural Resources and Life Sciences in Vienna, Austria (Scharf, et al., 2012) investigated the effectiveness of green roofs in protecting a building's envelope from heat gains. They looked at three extensive roof greenings with substrate depths of 120mm and one intensive green roof with a deeper substrate of 300mm.

Figure 1 The Test beds in Vienna (B.Scharf, 2012)

These were compared to three types of conventional roofs, consisting of gravel, bituminous foil and tin. The study concluded that the green roofs protected the building significantly better than the standard roofing types although it was found that excessive solar temperatures did reduce their effectiveness as it tended to dry out the substrate. In dry conditions, the daily amplitude of a dry green roof rose up to $17^{o}C$ measured on the building envelope while the tin roof recorded a daily amplitude of $55^{o}C$. Following rainfall, the amplitude on the green roof fell to $7^{o}C$, while on the tin roof the reading still amounted to $40^{o}C$. In conclusion, it was shown that green roofs are *"…an attractive solution to improve the thermal comfort of cities"* (Scharf, et al., 2012). The effect of moisture within the substrate and depth of substrate are features that were investigated as part of the LifeMedGreenRoof Project and the results are discussed later in this report.

The use of Computer Modelling to assess Thermal Performance of green roofs.

Ninbo, China (University of Nottingham)

A number of studies have focused on the use of computer modelling in order to predict the performance of green roofs. The advantages of modelling various scenarios against experimental methods are obvious. Experimental work can be expensive, time consuming and the results are specific to the location and therefore cannot be straightforwardly generalised. Research carried out at the Centre for Sustainable Energy Technologies (CEST) within the University of Nottingham aimed to describe the methodologies for the development of databases that include data inputs that could be used within building simulation programs in order to appraise the performance of green roofs. Via its use, the thermal performance of any building can be calculated.
Although, the application of a computer simulation program to model the performance of a green roof system has obvious benefits, the LifeMedGreenRoof Project has relied on empirical investigation.

Pittsburgh USA

Beyond Europe, much research has been undertaken in North America. In one investigation carried out at the Carnegie Mellon University in Pittsburgh, USA, researchers aimed to quantify the effect on heat transfer of two green roofs located on two separate buildings on the University Campus. Temperature sensors were placed within different layers of the green roofs. The readings taken from the thermal sensors were combined with information about the thermal properties of the layers in order to quantify the conductive heat transfer through the systems. The conductive heat transfer through the two green roof systems was compared to the performance of conventional concrete slab roof areas located adjacent to the green roof areas. Pittsburgh's climate is markedly different to that of Malta as the climate chart below (2.2) shows.

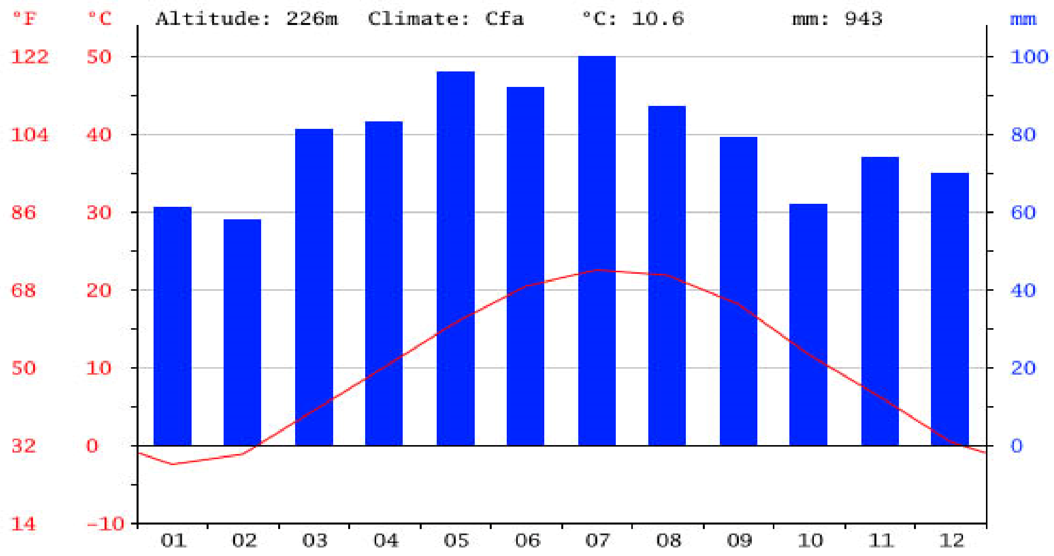


Figure 2 Annual Climate graph of Pittsburgh, USA,

During the winter months, (November to March) the temperature regularly falls to below 0°C. Not surprisingly the Pittsburgh research looks at both the cooling and heating properties of green roofs. It found that the green roofs on average lost 8.2% less heat than the conventional roof in the heating months and gained 75% less heat in the cooling months. This is a significant finding. This research methodology has parallels with the current LifeMedGreenRoof study in that the thermal performance of a green roof is compared to that of an adjacent conventional roof and that the performance of the green roof is evaluated by the use of thermocouples placed at different levels. However, the LifeMedGreenRoof study has concentrated on the cooling performance of the green roof as this feature is of greater relevance in relation to the particular climate of Malta.

Austin, Texas - USA

Austin in Texas has a markedly different climate to the more northerly Pittsburgh described above. It is characterised as having a humid subtropical climate with very long, hot summers, warm transitional seasons and short mild winters; which interestingly is very similar to Malta. An investigation into the hydrological and thermal performance of six different extensive green roofs was carried out by the University of Texas around Austin. The researchers suggest that the potential of green roofs to retain storm-water and to lower the thermal loading on buildings were attributes that could be particularly useful in subtropical climates such as Texas and for that matter Malta, which experience high temperatures and intense rain events. The six, extensive green roofs were planted with native plants and their performance was compared to a non-reflective, black roof and a white, reflective roof. The results showed that there was little difference between the six designs of green roofs. The maximum green roof temperatures were cooler than the conventional roofs by 38ºC at the roof membrane and 18ºC cooler inside the building. These findings are compared to those archived by the LifeMedGreenRoof study later in this report.

National Research Council of Canada

Another North American study on the thermal performance of green roofs has been undertaken at the Institute for Research in Construction by the National Research Council of Canada (Liu, 2003). A Field Roof Facility (FRF) was set up at the council's Ottawa campus. This consisted of a roof separated into two equal parts by a median divider into a generic, extensive green roof and a modified bituminous roof. Both the green roof and the reference roof were instrumented and this allowed direct comparison of the thermal performance of each. The instruments measured the temperature profile within the roofing systems, heat flow across the roof profiles, solar reflectance of the roof surfaces, soil moisture content, the microclimate created by the plants and storm water runoff. A weather station was set up at the medium divider and local meteorological data such as temperature, relative humidity, rainfall and solar radiation were monitored continuously. All the sensors were connected to a data acquisition system for monitoring.

Figure 3 Photograph of the FRF in the NRC campus in Ottawa (2002). The median divider separates the Green Roof (right) and the Reference Roof (left). The weather station is located at the median divider. (Liu, 2003)

The FRF was operated over almost two years (November 2000 to September 2002) and the data gathered and analysed. The results showed that the extensive green roof with a depth of 159mm of growing media could reduce the temperature of the roof membrane significantly in the summer (Figure 4 below).

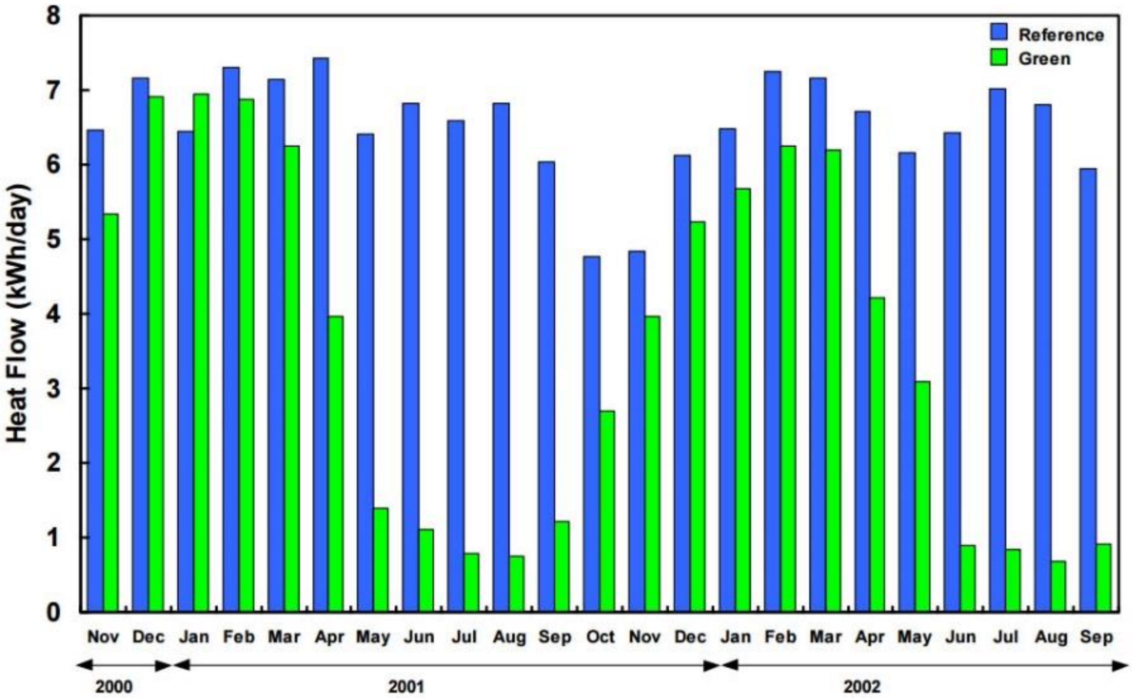


Figure 4 Heat flow measurements showing that the average daily energy demand due to the heat flow through the Green Roof was significantly less than that of the Reference Roof in the spring and summer. (Liu, 2003)

On the reference roof, temperatures of the exposed roof membrane reached over 70^{o}C in the summer but the membrane under the green roof rarely reached 30^{o}C. The heat flow through the roofing system of the green roof was also significantly moderated during the summer months.

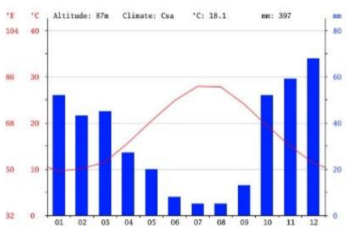
It was calculated that the average daily energy demand for space conditioning due to the heat flow through the roof was reduced from 6.0-7.5kWh/day to less than 1.5kWh/day as measured on the reference roof and green roof respectively. This corresponds to a reduction of over 75%.

It was noted that the green roof was more effective in reducing heat gain than heat loss. As Ottawa is in a predominantly heating region the researchers suggest that the effectiveness of a green roof would be more significant in regions experiencing warmer conditions such as Malta. The set-up of the Canadian study has significant parallels with the investigations carried out by the LifeMedGreenRoof Project in Malta and comparisons between the two studies will be discussed later in this report.

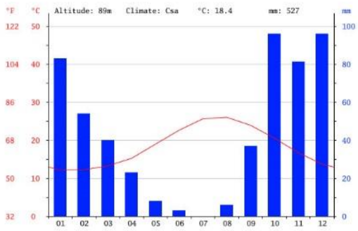
2.3 Research into Thermal Performance in the Mediterranean Region - Three Case Studies

Three case studies from locations situated around the central Mediterranean region have been selected for closer examination. The locations are shown in Figure 2-5 below.

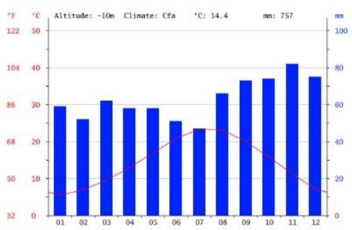
Figure 5 Showing the location of the three Case Studies selected. (Source; www.d-maps.com)



Athens, Greece



Malta (Birkirkara)



Ancona, Marche, Italy

Figure 6 Climatic graphs of the three locations selected as case studies

Although all three case studies are situated in central Mediterranean, as the graphs show their average rain and temperature conditions do vary (Figure 2-6). The climate of Ancona is humid subtropical and winters are cool.

Both Athens and Malta have similar climate profiles, both having 'hot summer Mediterranean climates'. It follows then that the predicted ability of green roof to cool living spaces in summer would be a welcome feature in all three locations.

The Marche Polytechnic University Study, Ancona, Italy

Ancona is a port city within the region of Marche and is located on the coast of the Aegean Sea. The green roof that was selected to be part of this study was located on the main building of the Regional Government of Marche. The study took place over the course of one year.

Figure 7 Aerial view of the port of Ancona in the region of Marche, Italy

The aim of research was to assess the energy related benefits of green roof in a Mediterranean climate by recording the thermal performance and energy efficiency parameters and comparing them with those recorded on a conventional slab roof. The study focused their data collection in summer when cooling of living spaces is most crucial.
The researchers first looked at the reduction of solar radiation due to the vegetation of the green roof. They compared the solar radiation incident on the horizontal surface and the solar radiation under the foliage of, in this case, the broom plants. They found that the foliage created a shadow on the soil surface thereby reducing the temperature and heat gain through the green roof layers.
The researchers also investigated the thermal performance of the green roof structure composed of the vegetation, growing media and drainage layer. This was done by evaluating the difference between the external surface temperature on the traditional roof and the temperature below the adjacent green roof. A sensor was positioned between the drainage and waterproof layer. The results are shown here in Table 1.

Table 1 Monthly average temperature at the external surface of the reference roof, under the soil, under the foliage and average dry bulb temperature observed at the green roof at the Regional Council of Marche (Italy) (Fioretti, R. 2010)

Table 2.1 - Month	External surface temperature (reference roof) (^{0}C)	Temperature under soil (^{0}C)	Temperature under foliage (^{0}C)	Dry bulb temperature (^{0}C)
June	28.37	22.54	22.02	22.89
July	30.10	25.11	24.99	25.82
Aug	31.72	24.46	24.89	25.65
Sept	23.23	20.78	18.05	18.81

It was evident from the analysis of the data that the green roof had a lower temperature level due to plant shading, insulation and evapo-transpiration from the foliage than the traditional reference roof.

The research moved to look at the effect that the green roof had on the internal environmental conditions. The demand for cooling of the interior rooms is dependant to a large extent on the heat flow through the building envelope and during summer by the absorption of solar radiation by horizontal surfaces which can produce a considerable heat load. The graph produced and replicated below compares the data collected from heat sensors beneath the green roof and with those beneath the conventional roof.

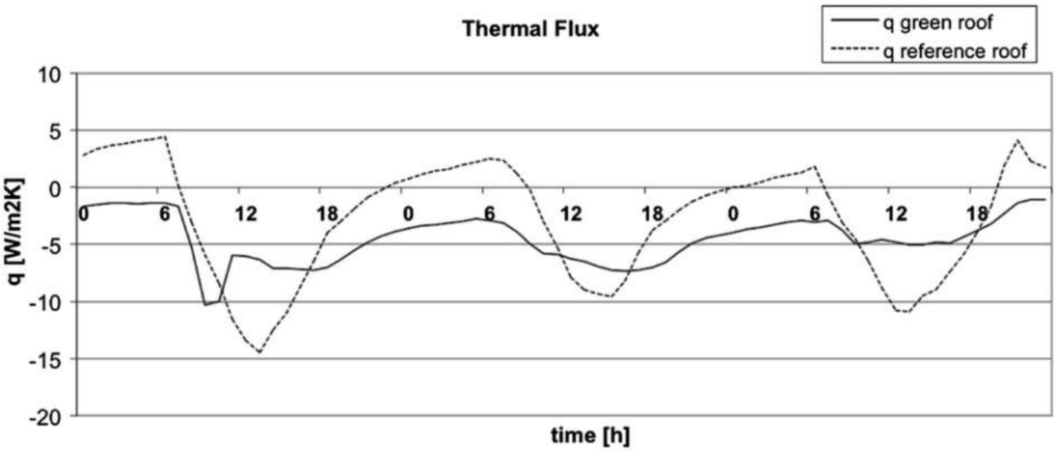


Figure 8 Heat flux measured on the internal surface of the green roof and the reference roof at the Regional Council of Marche (Italy). (R. Fioretti, 2010)

The above graph clearly shows the green roof's ability to moderate the fluctuations of the heat flux during summer and the report makes the point that the green roof has clearly outperformed the conventional roof in terms of reducing and moderating daily heat flows. Therefore, the potential for reducing the daily energy demand, particularly during the Mediterranean summer could be significant.

Investigation of the energy and environmental performance of a green roof installed in a nursery school in Athens, Greece

The climate of Athens is similar to that of Malta in that both are classified as hot summer Mediterranean climates. As with all urban areas, it suffers from the heat island effect where the ambient temperature is raised above that of suburban areas. However, due to recent accelerated industrialisation and urban development the effect is particularly strong in Athens. In fact, the city of Athens holds the World Meteorological Organization record for the highest temperature ever recorded in Europe, at 48.0 °C, which was recorded in the suburbs of Athens on 10 July 1977. (Athanasios & Sarantopoulos, 1977). The heat island effect is present in both summer and winter with mean daily intensity ranging between 6 and 12^{o}C for the city centre (Santamouris, 2001).

Figure 9 Aerial view of Athens. (Foster, J. 2015)

This Case Study is an investigation and analysis of energy and environmental performance of an experimental green roof system installed on a nursery school building in the centre of the city.
The investigation was carried out in two phases. The first phase took the form of an experimental investigation of the performance of the green roof system. The second phase involved a transient simulation program in order to calculate the cooling and heating load for summer and winter for the whole school building and for the top floor separately. Any energy savings that might result from the green roof's energy efficiency were also calculated.
In the second phase of the study the environmental and energy performance of the school building with the green roof was calculated using TRNSYS 15.1 Simulation Program (University of Wisconsin-Madison, 2002).
The results show that there was significant energy saving during the cooling period because of the significant outstanding reduction of the cooling load during summer. In contrast the influence of the green roof on the heating load during the heating period of winter was insignificant. The study emphasises this important point, that the effect on the winter heating load is insignificant. This is an interesting point to consider as normally, any intervention aimed at reducing cooling load of a building generally results in an increase in its heating load, but this is not the case with green roofs. In terms of heating and cooling loads, the percentage variations are summarised in Table 2 below:

Table 2 - Summary of cooling and heating load variation in % for the spaces beneath the green roof.

Table 2.2 Area of building	Type of load	Insulated/non-insulated	Percentage variation
Whole building	Cooling	Non-insulated	15% - 49%
" "	" "	Insulated	6% -33%
Top Floor	Cooling	Non-insulated	27% - 87%
" "	" "	Insulated	12% -76%
Top Floor	Heating		Very small

The study shows that green roof systems are predicted to provide significant environmental benefits including the potential to reduce the heat island effect. The urban roads and buildings absorb large amounts of solar radiation whereas in green and planted areas much of the incoming solar energy is used for the evaporation of moisture by the growing plants. The percentage energy savings shown here are echoed by the experimental study carried out at the Carnegie Mellon University in Pittsburgh USA. In comparing a green roof with a conventional roof they found that the green roof gained on average 75% less heat than the control roof in the cooling months of summer. (Becker & Wang, 2011)
In terms of the nursery school building itself, the simulations carried out by the study show that green roofs can make a significant contribution to building energy efficiency and that there is the potential to make remarkable and significant energy savings achieved through reduction of the summer cooling load. Therefore, the implementations of green roofs has the potential to enhance personal comfort by ameliorating the ambient air temperature and this also should result in a significant reduction in the use of conventional air conditioning and associated energy costs.

Life MedGreenRoof Project, Faculty for the Built Environment, University of Malta.

Figure 10 Aerial view of Lija, L-Iklin and Birkirkara, Malta (Vella, 2008)

The European Union's LIFE+ Programme is the EU's financial instrument supporting environmental and nature conservation initiatives. In October 2013, a decision was made to support a proposal to investigate the potential benefits of green roofs in a Mediterranean environment and to understand how climate influences their performance. The LifeMedGreenRoof project, proposed the installation of two green roofs, one at the Fondazione Minoprio near Milan in northern Italy and a second at the University of Malta. Both these green roofs have now been constructed and their function is to demonstrate the benefits of green roofs to the general public, building/design professionals and policy makers.

Figure 11 View of the Demonstration green roof at the Fondazione Minoprio, Italy (Author 2015)

Although the locations of the studies mentioned above have different climates to Malta, the evidence does show that it is possible to reap the benefits of a green roof within the Mediterranean context where it is often presumed that conditions are less favourable to the growth of plants on a roof.

One of the most significant economic benefits to people of the Mediterranean could be the potential, financial economies resulting from savings in energy use. As previously said, green roof can make a significant difference to heat gains experienced within the living space beneath. This means that personal comfort can be obtained with a lower use of mechanical air conditioning thereby reducing energy bills. However it has been pointed out that it is older properties that would benefit more from the installation of green roofs. This is because they

Figure 12 Visitors at the Demonstration Green Roof at the University of Malta (Author 2016)

generally have lower levels of insulation than is now demanded by modern building regulations (Castleton, et al., 2010). In 2010, the University of Michigan USA, carried out a valuation study comparing a 2,000m² conventional roof and a green roof (Getter, et al., 2011). They concluded that over its estimated lifespan of 40 years, a green roof would save about $200,000 (€179,284), of which nearly two-thirds would come from reduced energy costs. However, a point is made that variables such as the green roof design, its geographical location and surroundings and the building itself could have a significant effect on this cost saving estimate.

3 Investigations into the thermal performance of green roofs in Malta and Italy

3.1 Research carried out at the University of Malta (Phase 2)

Methodology

The experimental investigation carried out at the University of Malta was conducted in two parts, namely Phase 2 and Phase 3. In Phase 2, individual Test Trays, 1000mm x 1000mm x 250mm were set up to test the difference that substrate depth, soil moisture content, planting and type of plants could make to the thermal insulation performance of green roof set ups.

Figure 13 General photograph of the Test Tray experimental setup

Six Test trays were constructed from 12mm recycled plastic boards to form 1000mm x 1000mm x 250mm containers. These were supported on timber benches so as to provide access in order to attach the thermocouples to the sub-surfaces of the trays. Figure 4.5 below shows the general arrangement of the test trays. A 50mm thick sheet of expanded polystyrene was placed beneath the timber benches to cover the thermocouples to prevent the influence of fluctuating ambient air temperatures.
Each of the six trays were treated as shown in Table 3 below:

Table 3 A record of the contents of each Test Tray

Tray No	Planting media	Depth (mm)	Plants and species	Irrigated (litres per week)	Thermocouple location	
					Sub-base	Sub-surface
1	x				√	
2	√	200			√	√
3	√	100		9	√	
4	√	200	Pf*	18	√	√
5	√	200		18	√	√
6	√	200	Ss*	18	√	√

*Pf = Phlomis fruticosa. Ss = Sedum sediforme

Tray 1 was left empty and was the control in this experiment, this represented the equivalent of a basic empty roof surface. All the trays, including tray 1, were fitted with a thermocouple attached to the centre point of the underside base. All the other five trays were filled with 200mm of planting media, apart from tray 3 which was filled to half this depth. Two of the trays were planted with 16 native plants. The plants had been grown in the trays for eighteen months prior to the beginning of the experiment so they were well established and mature.

Tray 4 was planted with Phlomis fruticosa or Great Sage. It is a small evergreen shrub (semi-deciduous in summer) and can grow up to 1 m tall by 1.5 m wide. The sage-like, aromatic leaves are oval, 50mm to 100mm long, wrinkled, grey-green with white undersides, and covered with fine hairs. The white undersides and velvety texture of the leaves are adaptions to prevent the loss of moisture, however it is not a succulent. The leaves are held relatively high and cast a shadow on the soil surface. Tray 6 contains Sedum sediforme or the Mediterranean stonecrop. Its succulence is an adaption to water conservation. It also has an additional physiological adaption to survive particularly harsh, dry condition and that is Crassulacean acid metabolism, also known as CAM photosynthesis, This is a carbon fixation mechanism that evolved in some plants including Sedum species as an adaptation to arid conditions. In Sedum sediform the stomata in the leaves remain shut during the day to reduce evapo-transpiration, but open at night to collect carbon dioxide (CO_2). The sedum is a low spreading plant and has very nearly covered the whole surface of its test tray.

Irrigation was applied to all trays except trays 1 and 2. Tray 2 was kept dry to investigate the role of moisture in the transfer of heat energy through the green roof simulations. It could be directly compared to tray 5 which contained the same depth of planting medium but was irrigated.
Table 4 below lists the investigations that were the purpose of this series of experiments and indicates which trays were compared to provide evidence for the questions posed.

Table 4 Test Tray investigations

Investigation	Tray no	Compared to	Tray no
What difference does the depth of substrate make to the thermal insulation performance of a green roof?	3	>	5
Does increased moisture improve the thermal insulation performance of a green roof?	2	>	5
Do plants make a difference to the thermal insulation performance of a green roof?	5	>	4 & 6
Does the morphology of a plant make a difference to the thermal insulation performance of a green roof?	4	>	6

In addition to investigating the difference the various variables described above make to the thermal insulation performance of the green roof, it was also decided to investigate how two variables may affect the absorption of solar radiation at the surface. For this thermal couples were placed 20mm beneath the surface at the centre of Trays 2, 4, 5 and 6.

Table 5 Test Tray investigations of surface temperatures

Question	Tray no	Compared to	Tray no
Does increased moisture affect the degree absorption of solar heat at the surface of a green roof?	2	>	5
Does the morphology of a plant degree absorption of solar heat at the surface of a green roof?	4	>	6

The examination set up of the Test Trays collected data covering two weeks from the 25th of August to the 8th of September 2016. However, it was found that the weather over this period was fairly constant. It has been decided that the data will be examined for two days, the 28th and 29th of August 2016. This was done to focus on the diurnal pattern at a closer magnification and so show a more detailed pattern more easily shown in the graphs of data.

Results and Analysis

Six investigations were proposed in order to assess the thermal performance of green roofs. The first question was devised to explore the difference that different depths of planting medium would make to the performance of the green roofs. Three trays were used and temperature readings were gathered from thermo-couples attached to the subsurface of each tray.

Investigation 1

Table 6 Test Tray set up of Investigation 1

Investigation 1. *What difference does the depth of substrate make to the thermal insulation performance of a green roof?*				
Tray No	Planting media	Depth (mm)	Plants and species	Irrigated (litres per week)
1	x			
3	√	100		9
5	√	200		18

The graph below (Figure 14) shows that the control, empty tray exhibited a wide, diurnal fluctuation in temperature from a low of 21.0^{o}C at 03:15 to 68.8^{o}C at 13:00. This is a range of 47.8^{o}C.

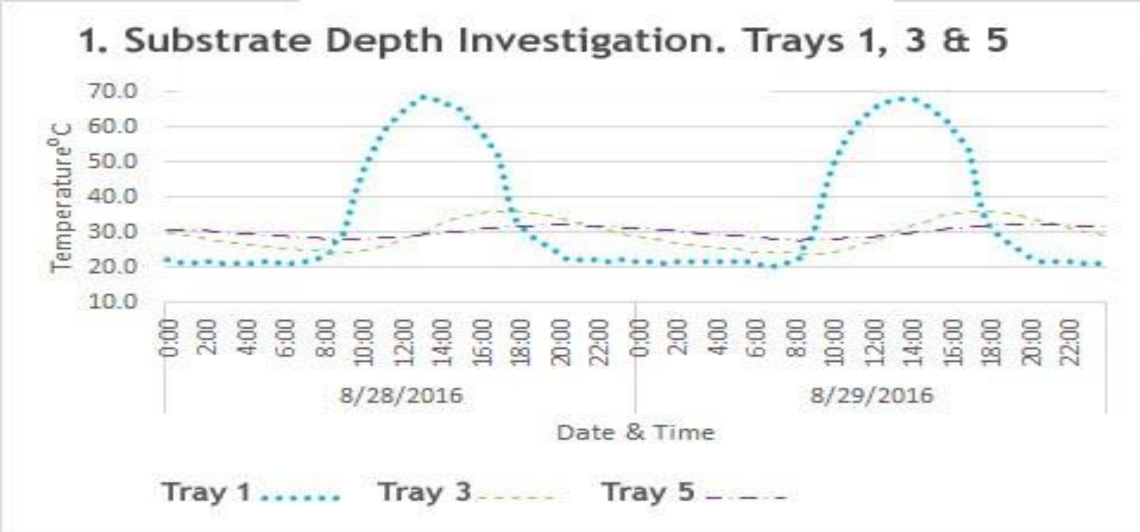


Figure 14 Investigation 1 - Comparison of solar gains in Trays 1, 3 & 5 of varying substrate depths over two days 28/08/16 and 02/09/16.

If data collected from the weather station adjacent to the Test Trays is examined it is possible to extract temperature levels of both the ambient air temperature and that of the nearby, conventional roof surface and compare these to those found for the control, empty Test Tray. Figure 15 below shows the external air and roof surface temperatures for the two days under consideration (28/08/16 – 29/08/16).

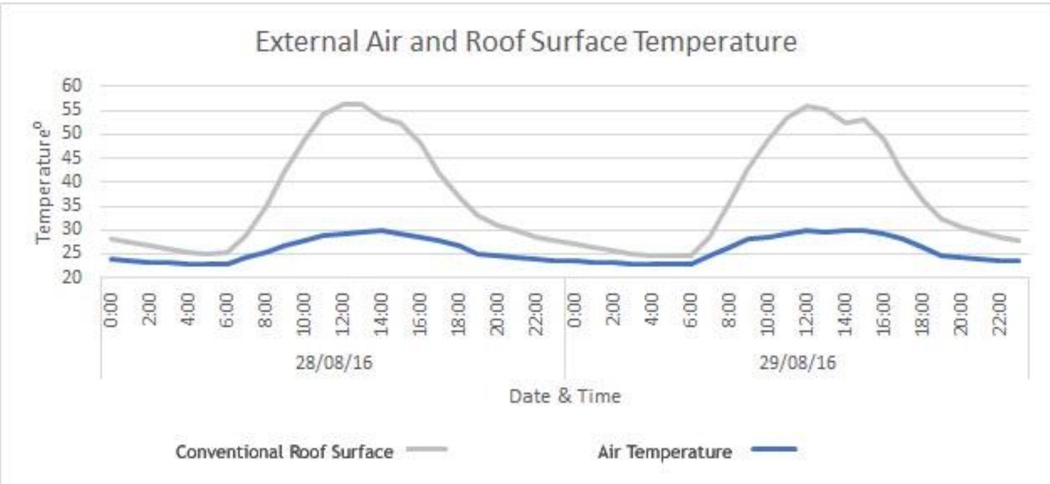


Figure 15 External Air and Conventional Roof Surface Temperatures

If the above ambient air and conventional roof surface temperatures are compared as in Table 7 below, it can be seen that the surface of the Test Tray heated up considerably more than the surface of the conventional roof. This is probably due to their thickness and construction. The Test Tray base consists of a relatively thin (12mm) recycled plastic sheet coloured black; the conventional roof consists of a 430mm thick concrete slab covered by a black bitumen waterproof layer. The mass of the conventional roof would stabilise temperatures somewhat, and help prevent the substantial temperature range exhibited by the empty Test Tray 1. This is a factor that needs to be taken into account when comparing different temperature ranges of the Test Trays as their absorption of solar radiation is not that of a conventional roof surface.

Table 7 Range of Temperatures of Ambient Air and conventional Roof Surface compared to the Subsurface of empty Tray 1.

Tray No.	**Condition**	**Lowest temp. °C & (time)**	**Highest temp. °C & (time)**	**Range**
1	Empty	21.0°C (03:15)	68.8°C (13:15)	47.08°C
Conventional Roof Surface		25.01°C (05:00)	54.08°C (11:00)	29.07°C
Ambient air temp		22.76°C (05:00)	29.75°C (14:00)	6.99°C

In considering the graph above (Figure 14) the presence of planting media within the boxes dramatically reduces the solar gain even if only half full as in Tray 3. In fact, there is little difference between the half-filled tray and the full tray when compared with the empty tray. However, as discussed above, the capacity of the Test Tray surface to gather solar radiance is not that of a conventional roof surface and so direct comparisons cannot be made here. Nevertheless, the thickness of the planting medium does improve the insulation properties of green roofs and the thermal range of the full Tray 5 is shown to be 36.4% less than the half empty Tray 3. The range of temperatures is listed in Table 8 for ease of comparison.

Table 8 Investigation 1 - Range of Temperatures in Trays 1, 3 and 5

(1) Tray No.	**Condition**	**Lowest temp. °C & (time)**	**Highest temp. °C & (time)**	**Range**
1	Empty	21.0°C (03:15)	68.8°C (13:15)	47.8°C
3	½ full, Irrigated	24.4°C (8:15)	36.3°C (17:15)	11.8°C
5	Full, Irrigated	28.0°C (8:15)	32.3°C (19:15)	4.3°C

It can be seen from Table 3.6 that even the half full Tray 3 is considerably more efficient at preventing solar gain at the Tray surface than the empty Tray 1. The data also shows a delay in heating and cooling as a result of the insulation of the growing medium. Trays 3 and 5 did not reach their lowest temperature until five hours after Tray 5. And Trays 3 and 5 did not reach their highest temperatures until 4 and 5 hours respectively, after Tray 5.

Investigation 2

The second investigation looked at the effect that moisture could have on the thermal performance of a green roof. Two full Trays, 2 and 5 were monitored for heat gain. Tray 2 was not irrigated whist Tray 5 received 18 litres a week delivered in episodes of 6 litres per day on three alternative days of the week (Table 9).

Table 9 Test Tray set up of Investigation 2.

Investigation 2. *Does increased moisture improve the thermal performance of a Green Roof?*					
Tray No	*Planting media*	*Depth (mm)*	*Plants and species*	*Irrigated (litres per week)*	*Moisture reading*
2	*√*	*200*			
5	*√*	*200*		*18*	

The graph shown in Figure 16 below shows that the irrigated Tray 5 is almost two degrees lower in peak temperature than the non-irrigated Tray 2. The temperature rise and fall in Tray 5 is also more gradual than in Tray 2. The reason for this could be that energy is used in the irrigated tray to evaporate the increased moisture and so the temperature at the base of the tray is reduced. The comparative temperatures are given in Table 10 below.

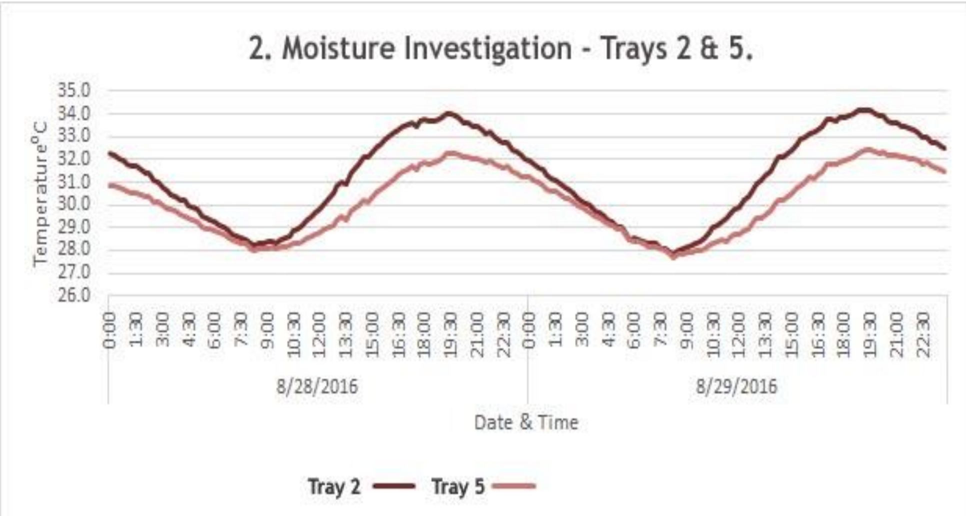


Figure 16 Investigation 2 - Graph comparing Thermal performance of Trays 2 (Dry) and 5 (Irrigated).

Table 10 Comparison of a dry substrate with an irrigated one

(2) Tray No.	**Condition**	**Lowest temp. °C & (time)**	**Highest temp. °C & (time)**	**Range**
2	Full, Dry	23.4°C (23:45)	34.6°C (06:45)	11.2°C
5	Full, Irrigated	23.0°C (7.45)	32.6°C (06:45)	9.6°C

Investigation 3

The third investigation was designed to assess the effect that planting had on the thermal performance of green roofs. In addition it was planned to look at two plants with different morphologies.

Table 11 Test Tray set up of Investigation 3.

Investigation 3. *Do plants make a difference to the thermal insulation performance of a green roof?*				
Tray No	Planting media	Depth (mm)	Plant species	Irrigated (litres per week)
4	√	200	Phlomis fruticosa	18
5	√	200	x	18
6	√	200	Sedum sediforme	18

Phlomis fruticosa, (Great Sage) is an upright plant with its sage like leaves held above the ground. It is partially summer deciduous so its shading of the ground is not as complete as Sedum sediforme (see Figure 17 below).

Figure 17 Plant species selected - Phlomis fruticosa and Sedum sediforme

Phlomis fruticosa

Sedum sediforme

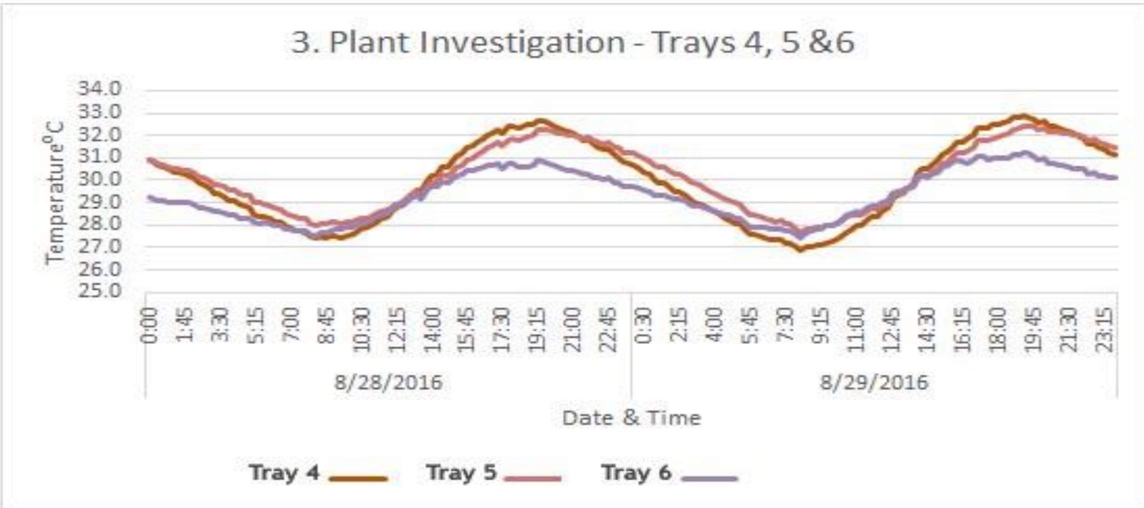


Table 12 Result of the plant investigation

(3) Tray No.	**Condition**	**Lowest temp. °C & (time)**	**Highest temp. °C & (time)**	**Range**
4	Full, Phlomis f.	27.4°C (8:15)	32.7°C (19:15)	5.3°C
5	Full, Irrigated	28.0°C (8:15)	32.3°C (19:15)	4.3°C
6	Full, Sedum s.	27.5°C (8:15)	31.2°C (19:15)	3.7°C

Figure 18 Graph showing the influence of plants on thermal performance.

The Sedum sediforme (Tray 6) appears to be more effective than the Phlomis fruticosa (Tray 4) in moderating fluctuations of temperature. If compared with the unplanted Tray 5, it can be seen that the Sedum in Tray 6 reduces the peak heat gain by about 1.5°C.

Interestingly it also appears to prevent the loss of heat at night showing an increase of 1°C over the unplanted Tray 5. This could be a result of the completeness of cover of the Sedum over the surface of the Tray.
The base of Tray 4 containing Phlomis fruticums heats up from about 01:00 to 19:00 but then cools down more rapidly and stays cooler than the other two boxes during the night.

Investigation 4

In this investigation it was decided to look at whether the morphology of the plants made any difference to the thermal performance of the green roof.

Table 13 Test Tray set up of Investigation 4.

Investigation 4. *What difference does the morphology of plants make to the thermal performance of a green roof?*				
Tray No	Planting media	Depth (mm)	Plants and species	Irrigated (litres per week)
4	√	200	Phlomis fruticosa	18
6	√	200	Sedum sediforme	18

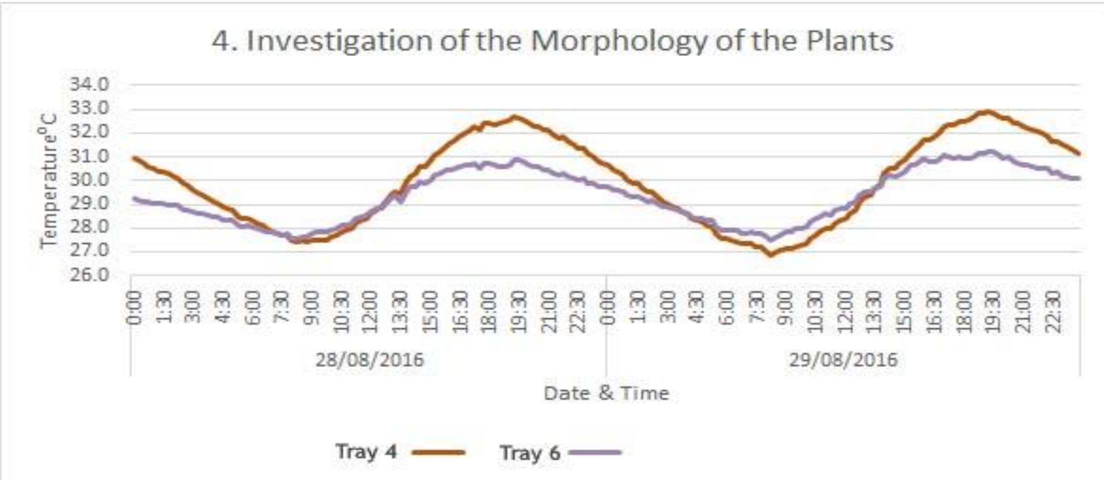


Figure 19 Graph comparing the thermal performance of two plants of varying morphology.

Table 14 Result of the plant investigation 4.

(4) **Tray No.**	**Condition**	**Lowest temp. °C & (time)**	**Highest temp. °C & (time)**	**Range**
4	Sedum sediform	27.5(08:15)	31.2 (19:15)	3.7°C
6	Phlomis fruticosum	28.0(08:15)	32.3 (19:15)	4.3°C

It appears from the above graph that the Sedum sedifolium in Tray 6 is able to modify temperature fluctuations more effectively than Phlomis fruticosa in Tray 4. This could be due to their morphology. Phlomis fruticosa is a more upright shrub and is therefore less efficient in shading the surface of the substrate than Sedum sedifolium which has a creeping nature and is effective in covering almost all the planting medium.

Investigation 5

Two Test Trays were selected, one was kept dry (Tray 2) and the other was irrigated with 18 litres per week (Tray 5) as was the case with the planted boxes.

Table 15 Test Tray set up of Investigation 5.

Investigation 5. *Does increased moisture affect the degree of solar heat gain at the surface of the planting medium?*				
Tray No	Planting media	Depth (mm)	Plants and species	Irrigated (litres per week)
2	√	200		
5	√	200		18

Figure 20 shows the results in graph form while Table 3-14 provides the comparable data.. The graph clearly shows that the irrigated Tray 5 was more effective in prevention of heat gains during the peak heating period. This is likely to be due to thermal energy being used to evaporate moisture from the surface of Tray 5, energy is require to change the state of the water contained from liquid to its gas form or vapour, a process known as the 'latent heat of vaporisation' (Cutnell & Johnson, 2013) . The evaporation of water would effectively cool the surface of the planting media in Tray 5.

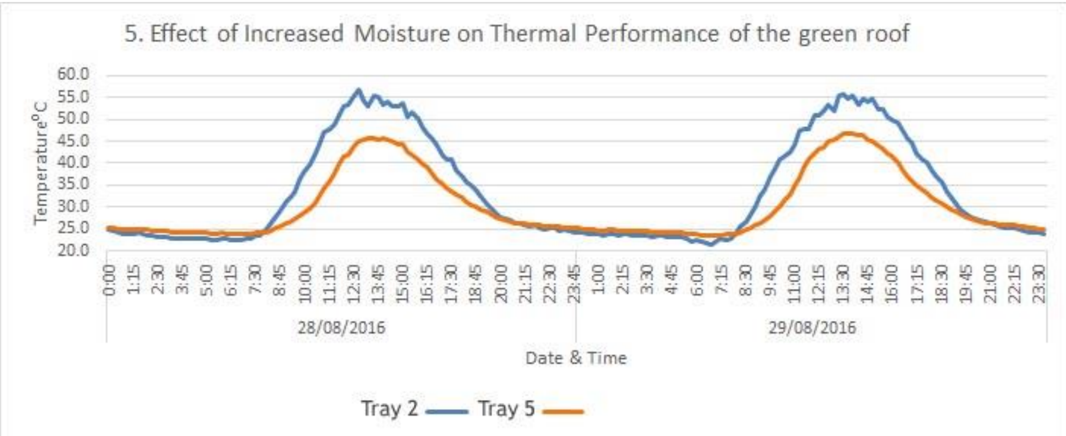


Figure 20 Graph showing the effect of moisture on the absorption of heat at the surface of the planting medium

Table 16 Comparing the temperature at the surface of the planting media in Tray 2 (Dry) and Tray 5 (irrigated).

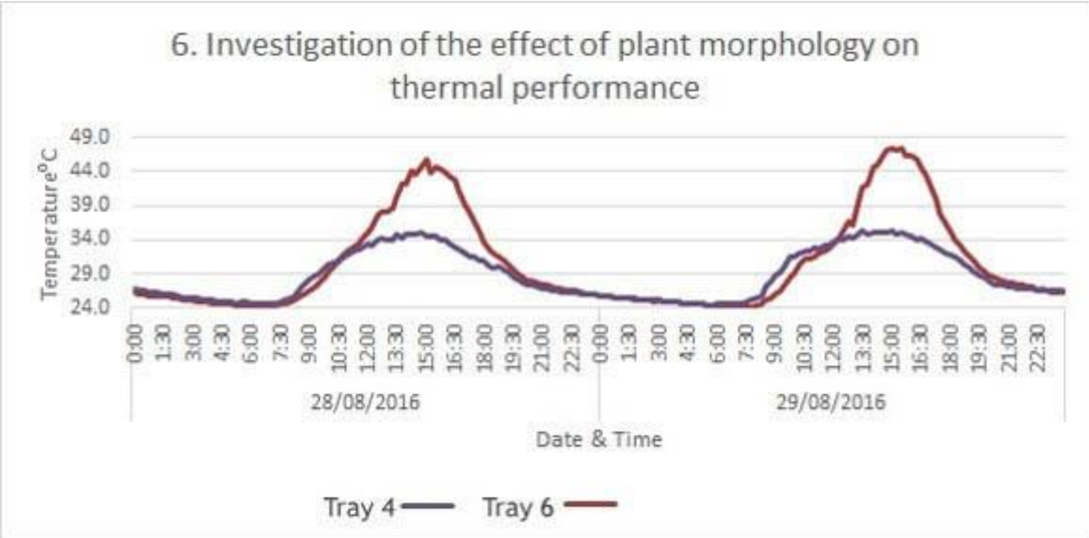
(5) Tray No.	**Condition**	**Lowest temp. ^{0}C & (time)**	**Highest temp. ^{0}C & (time)**	**Range**
2	Full, not irrigated	22.8 (06:15)	55.6 (12:00)	32.8^{0}C
5	Full, irrigated	23.0 (06:15)	46.4 (12:15)	23.4^{0}C

Investigation 6

Table 17 Test Tray set up of Investigation 6.

Investigation 6. *Does the morphology of different plants affect the degree of solar heat gain at the surface of the planting medium?*				
Tray No	Planting media	Depth (mm)	Plants and species	Irrigated (litres per week)
4	√	200	Sedum sediforum	18
6	√	200	Phlomis fruticosa.	18

Table 18 Graph showing the effect of different plant species on thermal performance



As with investigation 4, the Sedum sediform provided better insulation from solar heat gains at the surface of the growing media. It is thought that this is due to the more intense coverage of the growing media surface by this particular plant when compared to Phlomis fruticosa.

Comparing the effect that plant morphology has on the thermal performance.

(6) Tray No.	**Condition**	**Lowest temp. °C & (time)**	**Highest temp. °C & (time)**	**Range**
4	Sedum sediform	23.8 (07:30)	35.2 (15:10)	11.4°C
6	Phlomis fruticosum	23.5 (07:45)	48.4 (15:30)	25.0°C

Albedo values

It was also decided to take readings of the albedo range of the various surfaces investigated. The albedo of a surface is the fraction of the incident sunlight that the surface reflects. Radiation that is not reflected is absorbed by the surface. The absorbed energy raises the surface temperature. (J A Coakley, 2003) Albedo is measured on a scale from zero (no reflection) of a perfectly black surface to 1 for perfect reflection of a white surface. The closer to zero therefore means that more solar heat energy is likely to be absorbed by the surface. An albedometer was used during this study to measure the global radiation and the reflectance of the various surface under consideration.
The albedo is the ratio of these two measurements, that is global radiance divided by the reflectance gives the albedo value. In Figure 4-16, the albedometer is seen as set up, one meter above test tray 2. The albedometre was set up to take readings of 15 minute duration between 11:30 hrs and 12:45hrs on a cloudless day on the 18th of August 2016.
Global radiance and reflective radiance data was collected using an albedometer and these were used to calculate the albedo value for the various surfaces sampled. These surfaces and their albedo values are shown in Table 19 below.

Figure 21 Albedometer set up above test tray 2

Table 19 Surfaces sampled and their Albedo values

Time	Surface sampled	Albedo value recorded
11:30	Conventional roof membrane - black bitumen	0.08
11:45	Test tray 2 – planting medium only	0.33
12:00	Test tray 1 – empty – black recycled plastic/wood	0.1
12:15	Test tray 4 – Planted with Sedum sediforme	0.12
12:30	Test tray 6 – Planted with Phlomis fruticosa	0.2
12:45	Green Roof surface - planted	0.16

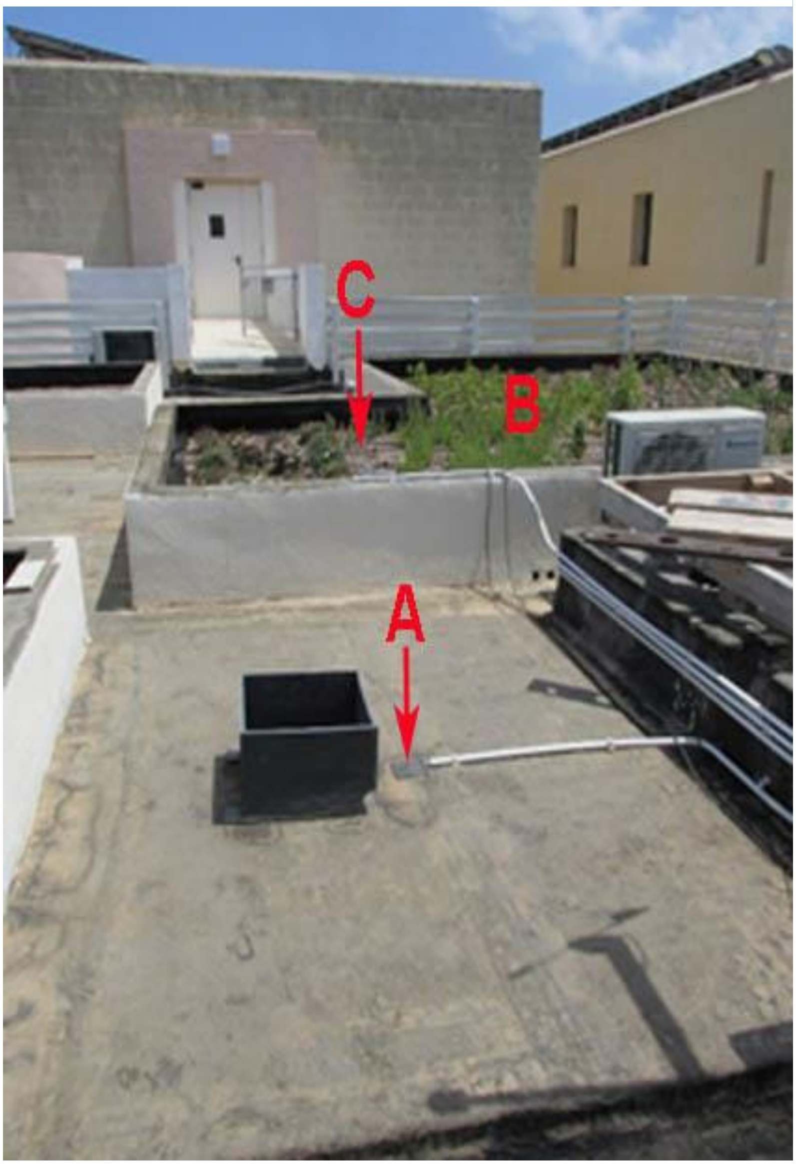
The recorded values show that the most absorbent surface was the conventional roof bitumen membrane followed closely by the uncovered surface of the test tray 1. The gravelled surface in tray 2 was the most reflective while the sedum covered tray 4 showed that plant foliage absorbs more of the radiated heat energy. Tray 6 planted with Phlomis fruticosm and the green roof were less densely planted than the Sedum tray and the greater reflectiveness increased their albedo values. This shows that green roofs can be useful in reflecting solar radiation, however it is the planting medium which is most effective.

3.2 Phase 3 - Investigation comparing the thermal performance of a conventional roof to that of a green roof (Malta)

Methodology

This investigation took place over a period of six months from the 1st of March until the 1st of September 2016. The main aim of the research was to compare the thermal insulation performance of an intensive green roof with that of a conventional concrete roof slab. The experimental set up is shown in Figure 22 below:

Figure 22 Photograph of Experimental Set up



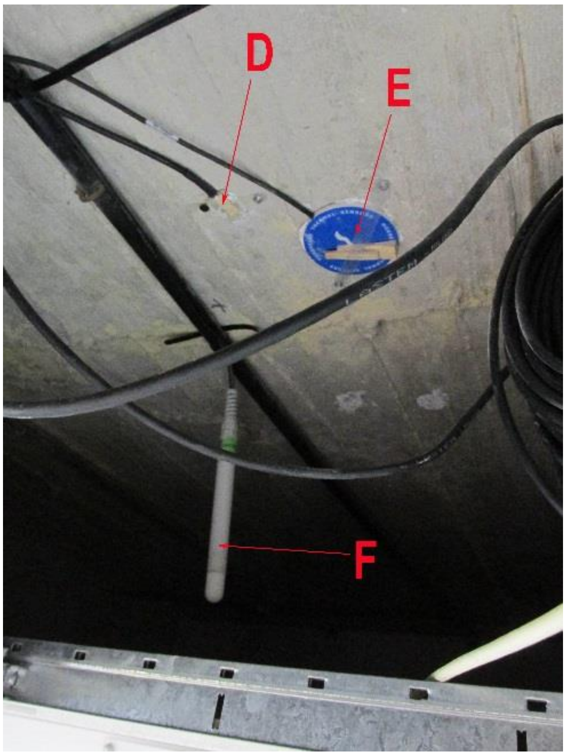
A = Thermocouple attached to the external surface of the conventional roof. An additional thermocouple and heat flux sensor were attached to the ceiling directly under this position (see Fig. 24).

B = Green Roof area

C = Location of soil surface temperature sensor (see Fig. 23) below for close-up). Directly beneath and attached to the ceiling at this point is a thermocouple and a heat flux sensor. There is also a sensor that records the air temperature under the soffit (see Figure 24 below).

Figure 23 Close –up photograph of soil surface sensor on the green roof

Figure 24 Photograph showing the thermocouple (D) and heat flux sensor (E) attached to the ceiling. 'F' is an air temperature sensor. Identical set ups were placed beneath



The location of the two sampling points, (the conventional roof and green roof) were 5 meters apart. The sensors beneath the roof slab were located above a false ceiling of expanded polystyrene tiles (15mm thick) above a non-conditioned corridor. However, air conditioned offices led into this corridor. In order to isolate the sensors attached to the ceiling further from the possibility of convectional heat influence within the false ceiling area, a box constructed from 50mm polystyrene was fixed around the sensors (Figure 25).

Figure 25 Photograph of Polystyrene box placed over the sensors attached to the ceiling

The sensors attached to the underneath of the ceiling fed data to a Model R - Radio data logger which in turn sent data wirelessly to a laptop computer (see Figures 26 and 27 below) The program used to record the data was the 'ESdat - Desktop / Environmental Data Analysis and Reporting Software' supplied by LSI LASTEM instruments.

Sensors recording data above the concrete roof slab were collected by a separate data logger that sent information by wired connection to the same laptop data program. This data logger also received data from the weather station located on the roof adjacent to the sampling points (Figure 26).

Figure 26 Model R – Radio Data Logger

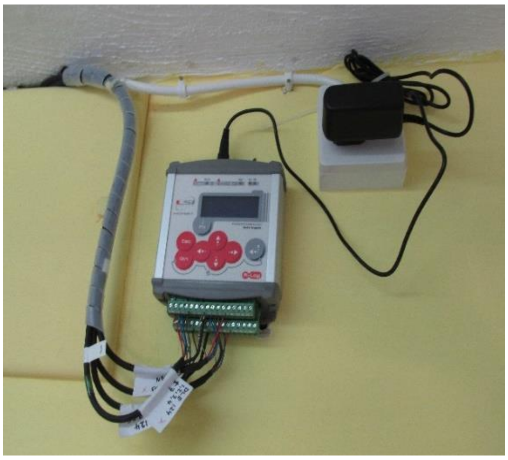


Figure 27 Data recorded on Laptop

The weather station recorded a comprehensive range of meteorological information. A brief description of the equipment used in this study is provided in Appendix A.

Figure 28   Weather Station located on green roof laboratory

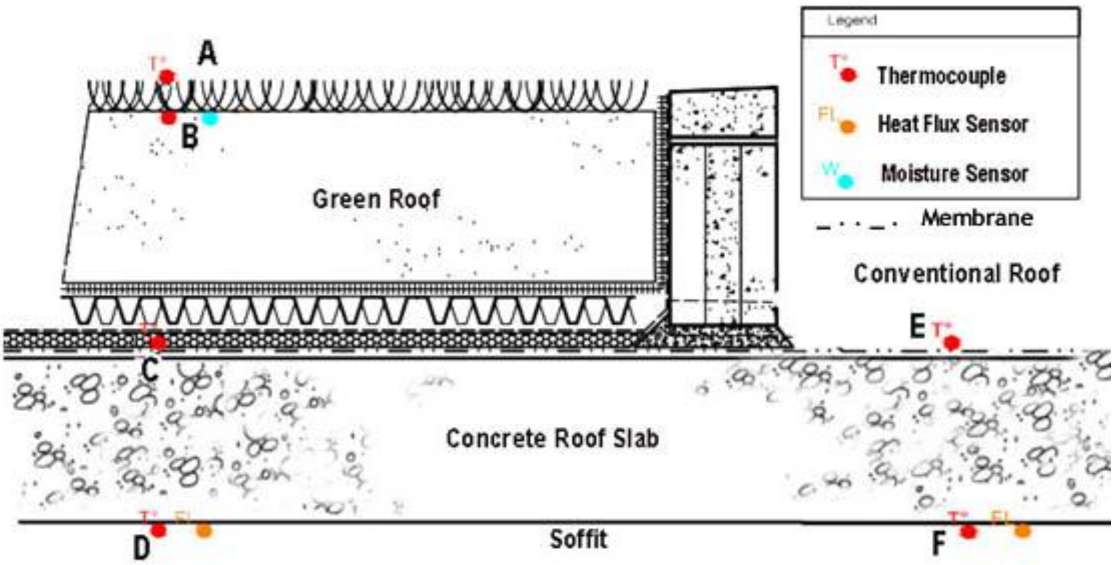
Data from each of the sensors was recorded at intervals of 10 minutes. In order to provide an early indication of the thermal insulation potential of the green roof a thermal imaging camera was used to sample the area around the two sets of sensors before the polystyrene box was fitted. (Figure 29)

Figure 29 Photograph of the author taking thermal images beneath the conventional and green roof soffit.

It was decided to take thermal camera images of the soffit under the conventional roof and the green roof in order to get an initial indication of the likely temperature ranges that could be expected. A FLIR E60 thermal camera was used to capture the images at noon on the 12th of May 2106.

In order to gather the required data a number of thermocouples, heat-flux sensors and a moisture sensor were located as is shown in Figure 30 below:

Figure 30 Diagram showing the location of the sensors used in relation to the Green Roof and Conventional roof



Results and Analysis

Data was recorded for 6 months from March to August inclusive in 2016. It was decided, firstly, to look at the temperature differences at the Soffit under the roof slab at location D (Green Roof) and F (Conventional Roof).
Before data was collected via the thermocouples, it was decided to take thermal camera images of the soffit under the conventional roof and the green roof in order to get an initial

indication of the likely temperature ranges that could be expected. A FLIR E60 thermal camera was used to capture the images at noon on the 26th of May 2106. The images taken are shown in Figure 31 below. The gradient bar to the right of the thermal image screen shows that the lighter the colour the warmer the temperature. It can be seen that thermal photographs taken of the soffits under both the conventional roof and under the green roof are of a similar tone although the soffit under the green roof was slightly darker and therefore cooler. At its greatest range the soffit under the green roof was found to be some 1.6^{o}C cooler than that measured under the conventional roof. This difference was regarded as disappointingly low when compared to the results obtained in other similar studies. Simmons et al (Simmons M. T., 2008) had shown, in investigations carried out at the University of Texas that the inside air temperatures under the green roof were 18^{o}C cooler than under a conventional roof. This difference is more than ten times that recorded in this study. It was thought that cool air was entering the corridor from the adjacent air conditioned offices and that this cooling was being transmitted through the 15 mm expanded polystyrene (EPS) false ceiling and affecting the temperature under the soffit. Boxes constructed of 50mm EPS were fixed to the soffit to cover the thermal instruments in order to eliminate the possibility of this cooling effect. However, the inclusion of the EPS made no difference to the results. Attention was then focused on the construction of the roof slab itself. When measured, it was found to be 550mm thick. The normal thickness of a concrete slab roof is between 150mm and 300mm therefore the thickness of the roof slab above the Faculty for the Built Environment was over twice the norm. It has been speculated that the roof is constructed on a concrete layer of conventional thickness i.e. 150mm to 300mm. This possibly could then have between 130mm to 180mm of 'Torba' laid on top and compacted and this could be covered with 100mm of concrete screed. Torba is a locally produced building material that consists of 'dust to 50mm' crushed limestone. It has a high thermal resistance value due to the air spaces it holds. It can be seen that the roof above the Faculty for the Built Environment could potentially have considerable thermal mass and resistance and this could be have a 'dampening' effect on the thermal influence of the green roof placed above it. Ideally, if further investigations of this type are to be carried out it would be best if a false concrete slab of conventional thickness were to be constructed as this would allow the recording of more meaningful data.

Figure 31 Thermal camera images

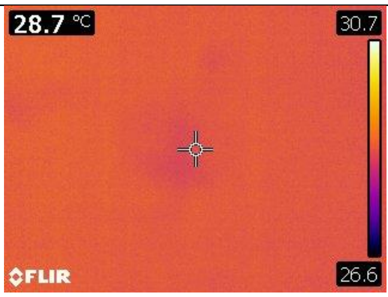
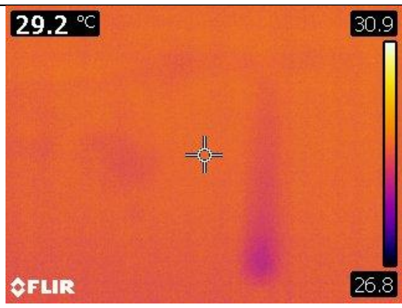
<table>
<tr><th></th><th>Image of Soffit under the Green Roof</th><th>Image of Soffit under the Conventional Roof</th></tr>
<tr><td>Conventional Image</td><td></td><td></td></tr>
<tr><td>Themal Image</td><td>
</td><td>
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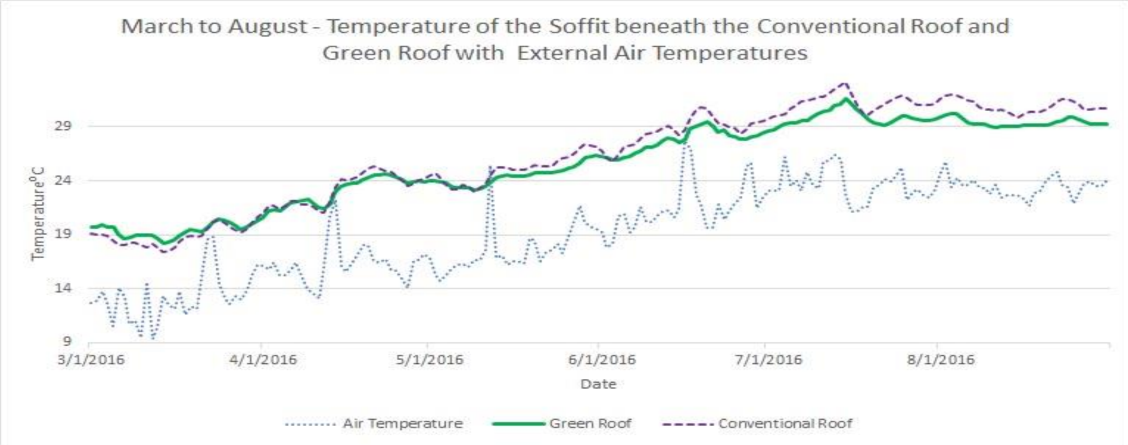
Figure 32 Graph comparing the temperature of the soffit beneath the Conventional Roof and Green Roof also showing the external air temperature



It can be seen that the ambient external air temperature gradually increases during the six month of sampling up to the end of August. It was also noticed that the temperature of the soffit under the green roof initially was warmer than under the conventional roof but this reversed as the weather got warmer that is, around 20°C. However the scale of this graph is too large to show detail and it was decided to look more closely at three periods during the sampling phase, i) during March at the beginning, ii) May and June in the middle and iii) August at the end.

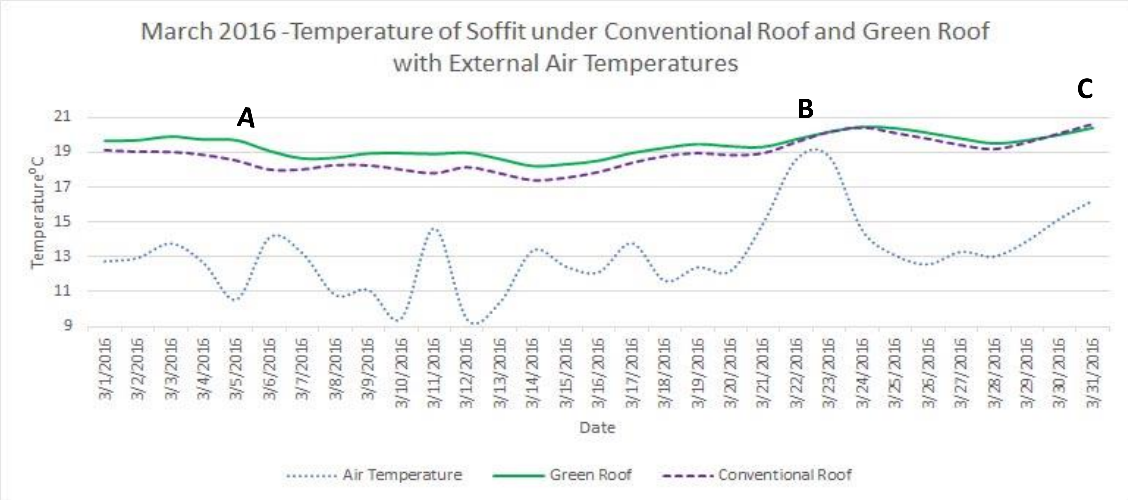
It was also noted from the graph that at around the middle of each month the air temperature showed a sudden and brief increase of 7°C on average. At first it was thought that this regularity must indicate a fault with the air temperature sensor. However closer examination of other temperature sensors such as that measuring the conventional roof membrane also showed a corresponding peak. In order to confirm the validity of the air temperature readings independent weather data for the study period was obtained from Malta Airport weather station located in Luqa some 7km south of the University (Figure 33).

Figure 33 Temperature Graph of the study period obtained from Malta Airport Weather station, Luqa. (Note the regular, monthly peaks in temperature which correspond with data obtained by the study).

Comparing the graph of the air temperature data from the airport weather station for the study period with the data recorded by this study it can be seen that the unusual peak temperatures correspond.

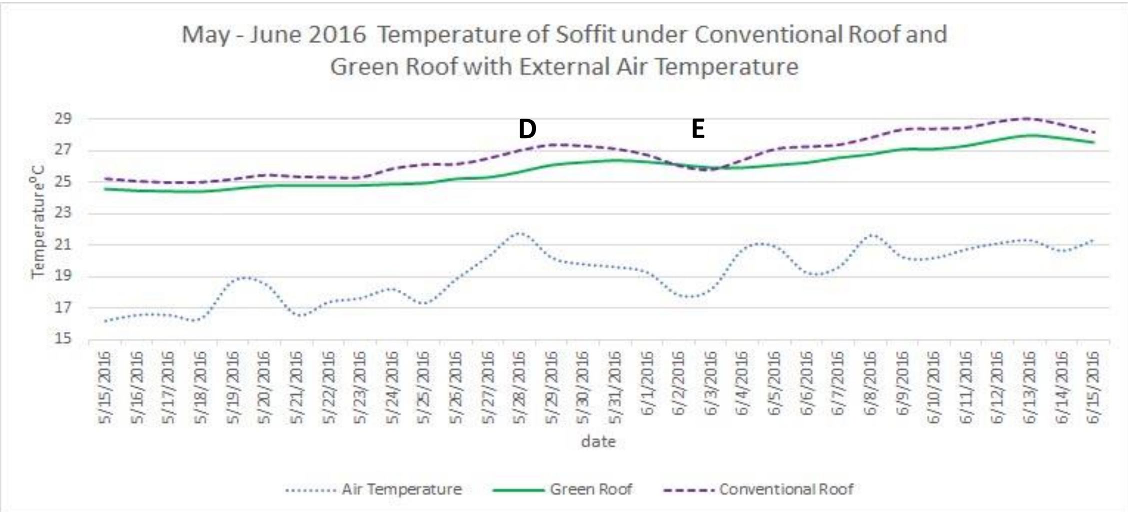
Figure 34 below shows that at the begin of March, which is regarded as a heating month with temperatures ranging from 9°C and 19°C, the soffit under the Green Roof was consistently warmer than that under the conventional roof. The largest difference was recorded at 1.27°C when the soffit under the Green Roof was at 19.95°C at 17:00 hrs. on the 4th of March (A). Later in the month, as the external air temperature started to rise above 19°C, the pattern began to reverse (B) and the soffit beneath the Green Roof became cooler by a maximum of 0.47°C at 23:00hrs on the last day of the month (C).

Figure 34 Graph showing the March temperature of the soffit beneath the conventional roof and green roof.



By the middle of the test period, that is from the 15th of May until the 15th June it was noted that the soffit beneath the green roof was consistently cooler than that beneath the conventional roof as shown in Figure 35 below. The maximum difference being 1.49°C at 05:00hrs. on the 28th of May 2016 (D). It can be seen that the green roof, in general, has a smoother, more uniform profile than that of the conventional roof. This suggests that its greater mass renders it more stable in resisting sudden or dramatic changes in temperature.

Figure 35 Graph showing the temperature between the 15th May and 15th June 2016 of the soffit under the conventional roof and the green roof.



At the end of the test period in August the ambient air temperature reached the highest external air temperature of 34.43^{o}C at 13:00hrs. on the 1st. of August. Again the green roof temperatures appear more stable.

Figure 36 Graph of the soffit temperature beneath the conventional roof and green roof with external air temperatures.

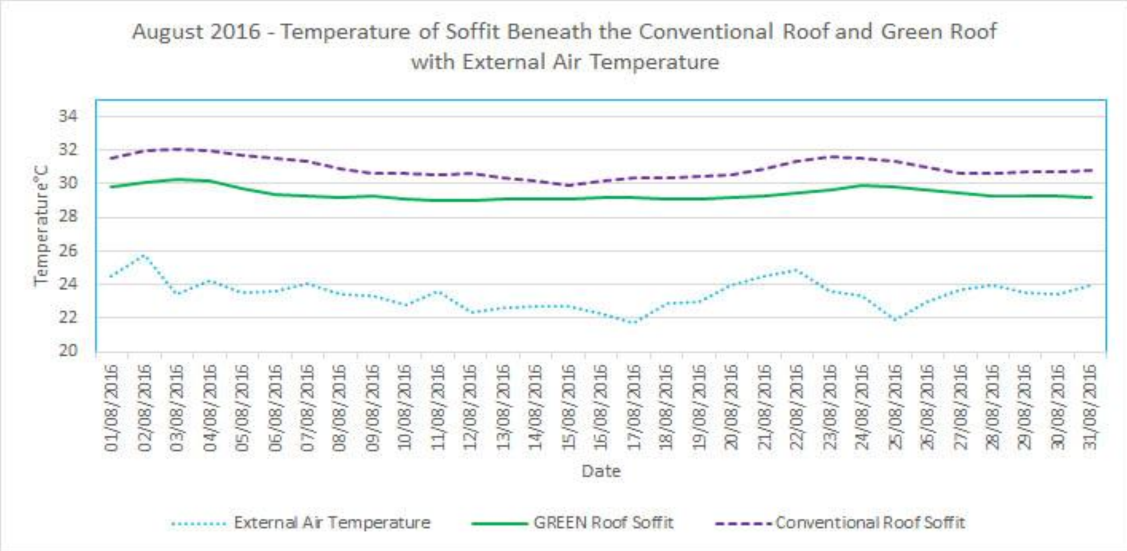


Table 20 below illustrates the range of temperatures measured under the soffit of the green roof compared to that of the conventional roof.

Table 20 Comparison of the Range of Temperatures Recorded beneath the soffit for the Green Roof and Conventional Roof.

	Green Roof Soffit	Conventional Roof Soffit
Highest Temperature (°C)	30.3	32.17
Lowest Temperature (°C)	28.97	29.82
Difference (°C)	1.33	2.35

This shows that the range of temperatures measured at the soffit beneath the green roof is 57% less than the range beneath the conventional roof.

Table 21 below shows the hourly temperature readings taken at the soffit surface beneath the green roof and conventional roof together with the external air temperature for one day, the 3rd. of August 2016. When the range of daily temperatures are tabulated it shows how relatively stable the temperatures of the soffit beneath the green roof was in comparison to the fluctuating external air temperatures. The range under the green roof is shown as being 0.09°C while that of the conventional roof was 0.27°C, three times the range of the green roof. The external air temperature in comparison exhibited a diurnal range of almost 5°C. It was noted also that throughout the investigation period the temperature as measured under the soffit at both stations was higher than the external air temperature. The reason for this is that the thermal mass of the concrete roof slab absorbs thermal energy and releases it slowly at night. This is the cause of the heat island phenomenon that has been discussed earlier. The added insulation effect of the green roof means that temperatures in the concrete slab do not rise as high and the range in temperature is more constant.

Table 21 Showing the complete record for temperature readings on the underneath surface of the green roof and conventional roof together with the external air temperature readings. for the 3rd of August.

DATE	TIME	EXTERNAL AIR TEMPERATURE	GREEN ROOF -SOFFIT	CONVENTIONAL ROOF - SOFFIT
		AIRTemp-M [2] Ave ('C)	TeSUFac1-S2 [19] Ave ('C)	TeSUFac2-S2 [20] Ave ('C)
03/08/16	00:00:00	23.46	30.25	32.05
	01:00:00	23.2	30.26	32.08
	02:00:00	22.9	30.26	32.1
	03:00:00	22.72	30.27	32.12
	04:00:00	23	30.27	32.14
	05:00:00	23.36	30.28	32.15
	06:00:00	23.94	**30.3**	**32.17**
	07:00:00	24.99	30.29	32.17
	08:00:00	25.95	30.28	32.16
	09:00:00	26.63	30.28	32.14
	10:00:00	27.1	30.28	32.12
	11:00:00	27.49	30.27	32.09
	12:00:00	27.43	30.28	32.07
	13:00:00	**27.65**	30.29	32.06
	14:00:00	27.53	30.27	32
	15:00:00	27.51	30.26	31.97
	16:00:00	26.88	30.24	31.93
	17:00:00	26.74	30.23	31.9
	18:00:00	25.93	30.23	31.9
	19:00:00	25.25	30.23	31.9
	20:00:00	24.9	30.23	31.9
	21:00:00	24.68	30.22	31.9
	22:00:00	24.55	30.22	31.91
	23:00:00	24.46	30.21	31.92

Table 5.9 below shows that the temperature range of the soffit under the green roof was 30% less than that under the conventional roof.

Table 22 Range of Temperatures of External Air and the Soffit beneath both the Green Roof and Conventional Roof

	Highest Diurnal Temperature (^oC)	Lowest Diurnal Temperature (^oC)	Range (^oC)
External Air Temperature	27.65	22.72	4.93
Green Roof Soffit Temperature	30.3	30.21	0.09
Conventional roof Temperature	32.17	31.9	0.27

Figure 37 below compares the diurnal temperature range of the conventional roof slab membrane with the membrane beneath the green roof structure on the 1st of March 2016. It can be seen that the range of temperatures displayed by the conventional roof membrane has a significant range of almost 23°C while the same membrane under the green roof is substantially reduced.

Figure 37 Range of Temperatures of External Air and the Soffit beneath both the Green Roof and Conventional Roof

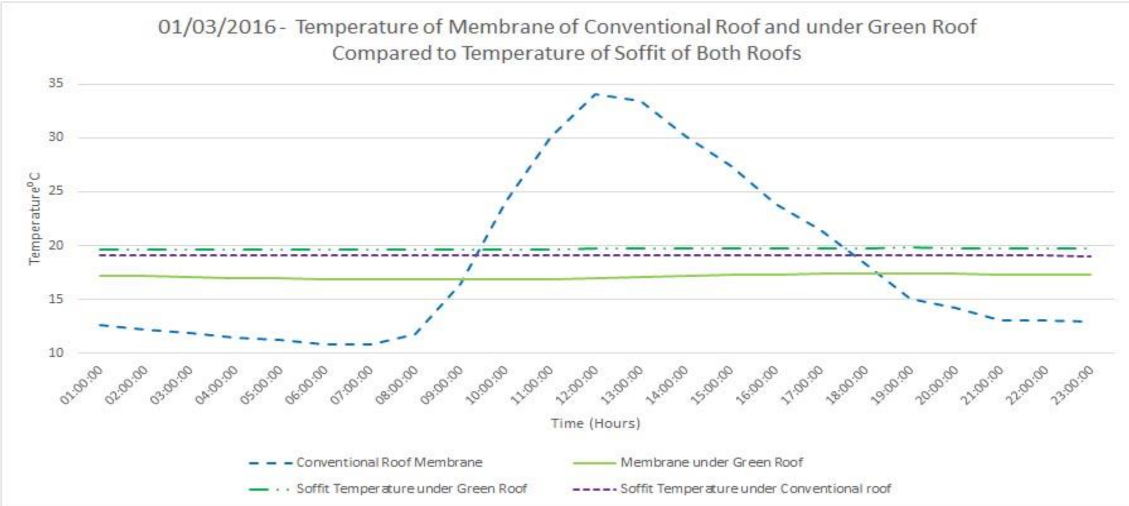


Table 23 Comparing temperatures of the membrane and soffit beneath the green roof and conventional roof.

01/03/2016	Highest Diurnal Temperature (°C)	Lowest Diurnal Temperature (°C)	Range (°C)
Membrane beneath Green Roof	17.41	16.83	0.58
Conventional Roof Membrane	34.06	11.20	22.86
Green Roof Soffit Temperature	19.80	19.62	0.18
Conventional Roof Soffit Temperature	19.14	19.04	0.10

When the data for the Conventional Roof Membrane is removed from the graph it can be seen more clearly that in the heating month of March the soffit beneath the green roof is warmer than the soffit beneath the conventional roof by about 1°C. However, both soffit temperature ranges are relatively stable compared to the green roof membrane (range =0.58°C) and particularly when compared to the conventional roof surface membrane (range = 22.86°C). This stability is a result of the insulator performance of the green roof structure and the thermal mass of the roof slab.

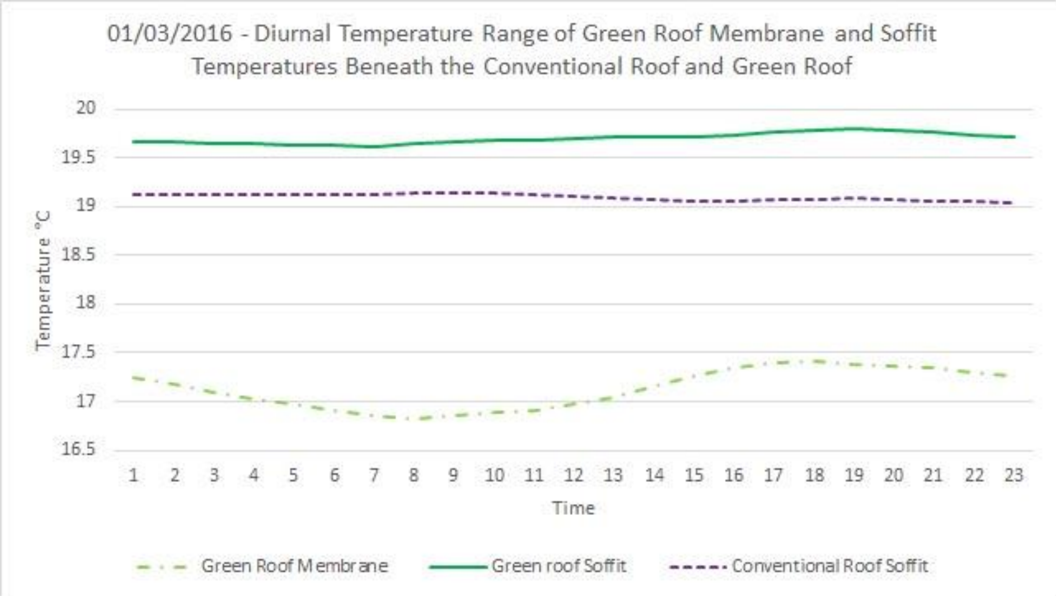


Figure 38 Graph of the diurnal temperature range of the green roof membrane and soffit temperatures beneath the conventional roof and green roof.

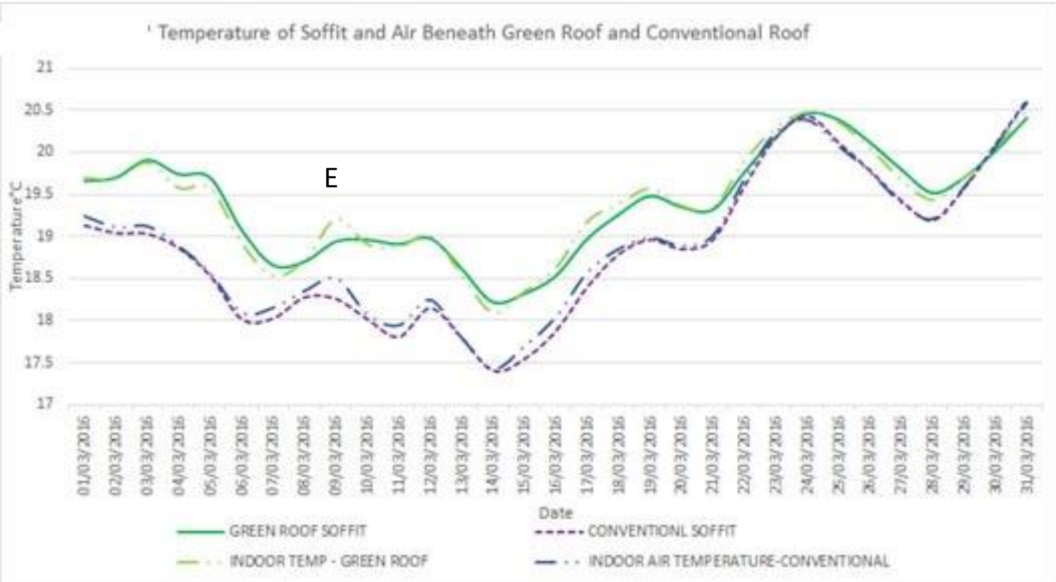


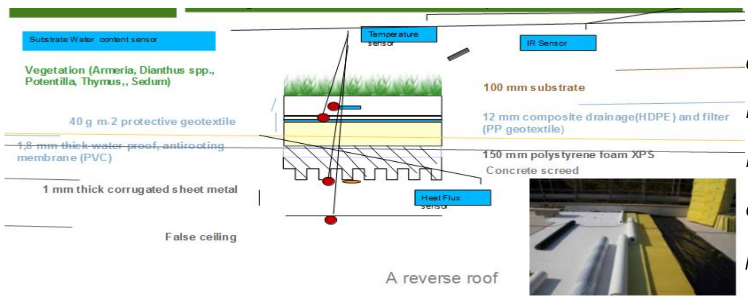
Figure 39 Temperature of Soffit and ambient air beneath green roof and conventional roof

Figure 39 above shows that the internal air temperature closely follows the temperature of the soffit beneath both the green roof and conventional roof. There is a small indication that the mass of the soffit stabilises the temperature as at point 'E' in comparison with the air temperature but on the whole the air temperature follows the soffit temperature. This suggests also that external temperature variation caused by ventilation or heating within the occupied office spaces is insulated from the sensors by the polystyrene, suspended ceiling and polystyrene enclosing box.

3.3 Research carried out at the Foundazione Minoprio, Italy

Methodology

This investigation took place over a period of twelve months from the 1st of July 2016 until the 30th of June 2017. The main aim of the research was to compare the thermal insulation performance of an intensive green roof with that of the reference one covered with 4 cm depth of gravel. The roof has been built in 2015 according to current regulations which require of a U-value (thermal transmittance) not higher than 0.24 for the geographical region “E”, in which Minoprio is located.



The reference roof was not covered by a green roof but by a layer of gravel. The photograph, bottom right, shows the structure of the reverse roof with insulation panels (yellow) placed on top.

Figure 40 Green roof Layers in Minoprio

The location of the two monitoring plots, (the conventional roof and green roof) were about 15 meters apart.

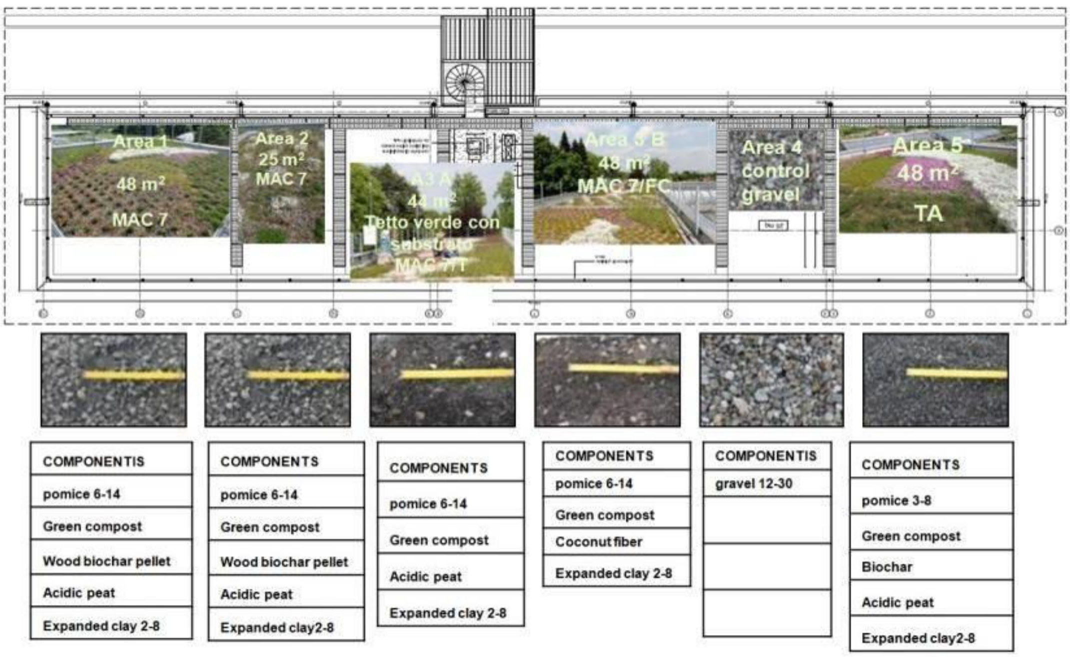


Figure 41 Plot layout of the Minoprio Green Roof, Area 2 is the GR monitored area, Area 4 is the reference area covered with gravel.

For each plot, a thermocouple was placed beneath the waterproof membrane, another one just under the sofit under the steel sheet and one on the false ceiling. Room temperqture sensors were placed on the inner wall 2 m height. Heat flux sensors were placed under the metal sheet.

In the Green Roof plot a temperature sensor coupled with a soil moisture sensor (TDR type) was placed in the middle of the substrate at 5 cm depth.

A second monitoring area waas placed upon the “building 15” of the ABC Departement of the Politecnico of Milan and a urban environment. In Fig. XX the layers and the sensor are shown.

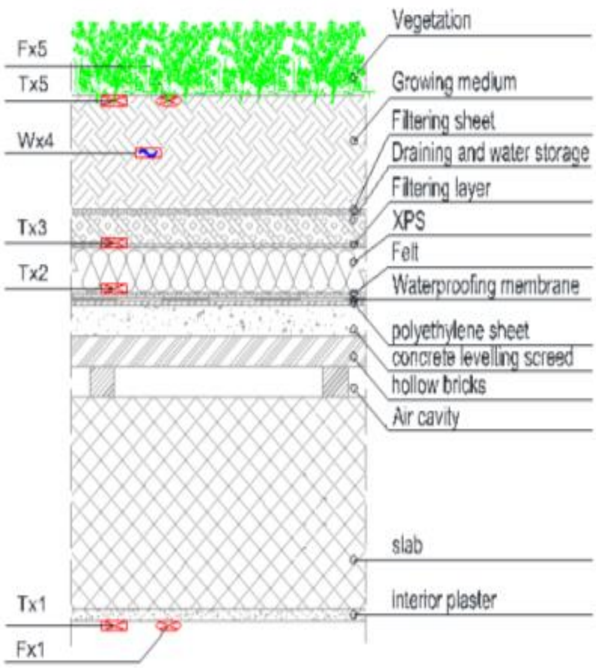


Figure 42 Green roof layers in Politecnico: the monitored plot has the same drainage and filter layer, the same growing media as well as its depth (10 cm) and vegetation as the green roof in Minopri

The roof was equipped with a meteorolical station to acquire environmental data (air temperatures and humidity, global and relected radiation, wind direction and speed).
A linux embedded datalogger recorded the data from the meteorological station and from the sensors every 10 minutes and sent them to a linux server by the lan connection. By means of the R statistical software, received data is inserted in a MySQL database. Thanks to R scrips, data is updated hourly and plots are stored in a DMZ server area that allows their automatic display on the server pages of the project.
In Politecnico the data acquisition is much like that utilised at the Faculty for the Built Environment in Malta.

Albedo values

During the 2016 data was collected concerning albedo values of selected surfaces on the experimental roofs.

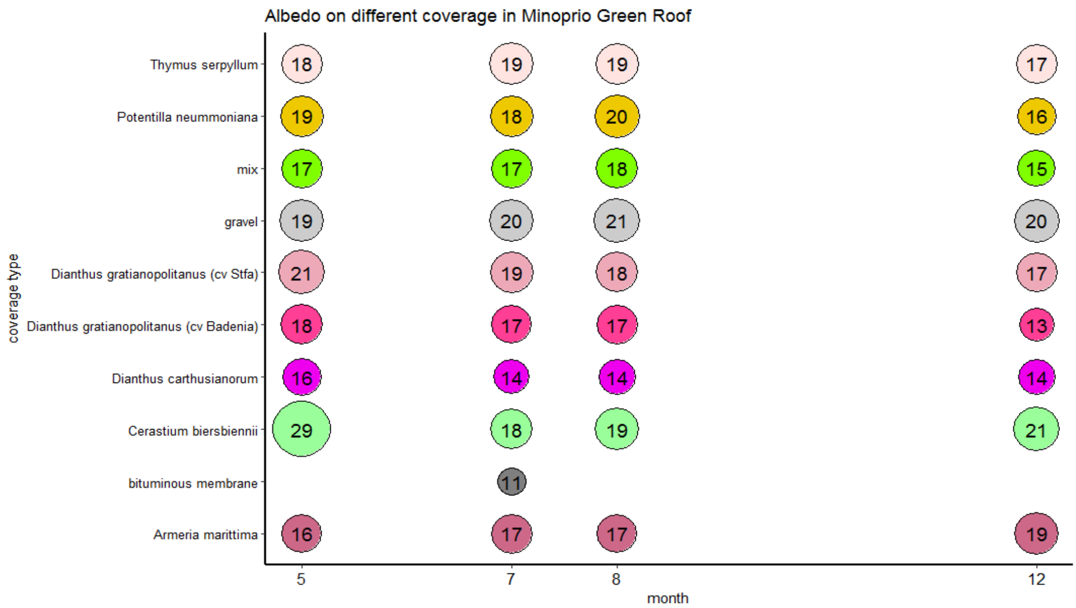


Figure 43   Albedo recorded on various surfaces on the roof at Foundazione Minoprio.

In Figure 43 above, data is reported according to coverage type and months and it is shown that plant reflectance is dependent not only on the species but also on the time of year. Reference bitumen surface reported the least reflection, as expected, only 0,11 ratio, the gravel reference roof recorded a 0.20. Different types of gravel and their humidity could change this value.
Between the species observed, white flowering (Cerastium) and light pink (Dianthus gratianopolitanus cv Stafa) gave best result in May, the time of their flowering. In the case of Cerastium a 0.30 reflection is almost reached. This species looses part of its reflecting capacity in summer due to the drying of basal leaves, and enhances it due to its light green leaves. Thymus increases its reflectance in summer, when it starts to flower (light pink color). Due to vegetation dessecation, in winter its value deceases. The coverage seems to play a role in case of potentilla which reaches a maximum and Analysis in summer, both in coverage and in albedo.

Results and Analysis

Thermal data

Data has been collected from Green roof plot (Area 2) and reference (Area 4) since March 2016. Heat flux sensors have not provided reliable data due, likely to 'interference' or contamination by the air conditioning and lighting services inside the false ceiling. Heat flux has then been calculated by means of thermocouples under the waterproof membrane and the ceiling according to Incroptera et al 2007.
Even the inner temperatures (room temperature and false ceiling ones) do not behave as expected because of the influence of other part of the building (walls and windows expecially) and of the imperfect North orientation of the building: in fact the longer sides are NNE and

SSW oriented. The reference roof is located to the east whilst the Green Roof is on the west side. Sun radiation is therefore not equally distributed.

Waterproof Membrane temperature

As is common with other studies, the main observations have recorded waterproof membrane temperatures and heat flux.
The behaviour of membrane temperatures is very different in the two plots monitored. On the reference roof, temperatures reach 60°C on the hottest days with internal air temperatures of not more than 30°C. The daily exernal temperature on these days reached more than 40 °C. Under the green roof the membrane temperatures reach only about 30 °C and the daily range is not more than 8°C, see Figure 44 below.

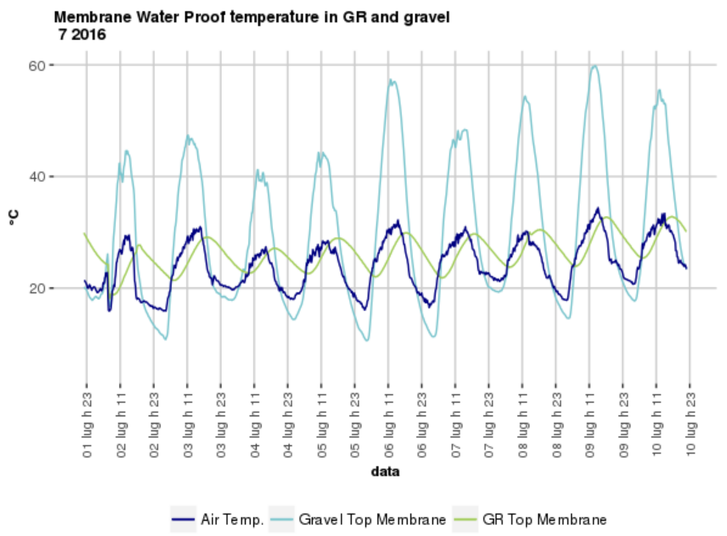


Figure 44 Summer membrane temperatures: extract of a ten day period in July 2016

In a day detail (Figure 45below) the peak of membrane temperatures is reached at mid-day on the reference roof, it is delayed till 5 pm in the green roof.

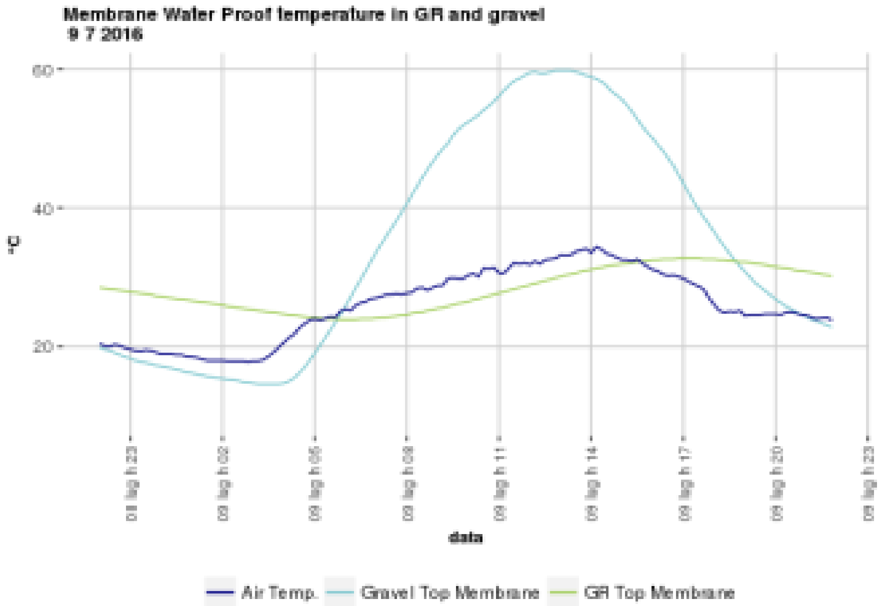


Figure 45 One day sample of Membrane temperatures in summer

During the winter, membrane temperatures excursion range in reference roof vary between 5 to more than 20 °C while in green roof vary from 0 to 5 °C.

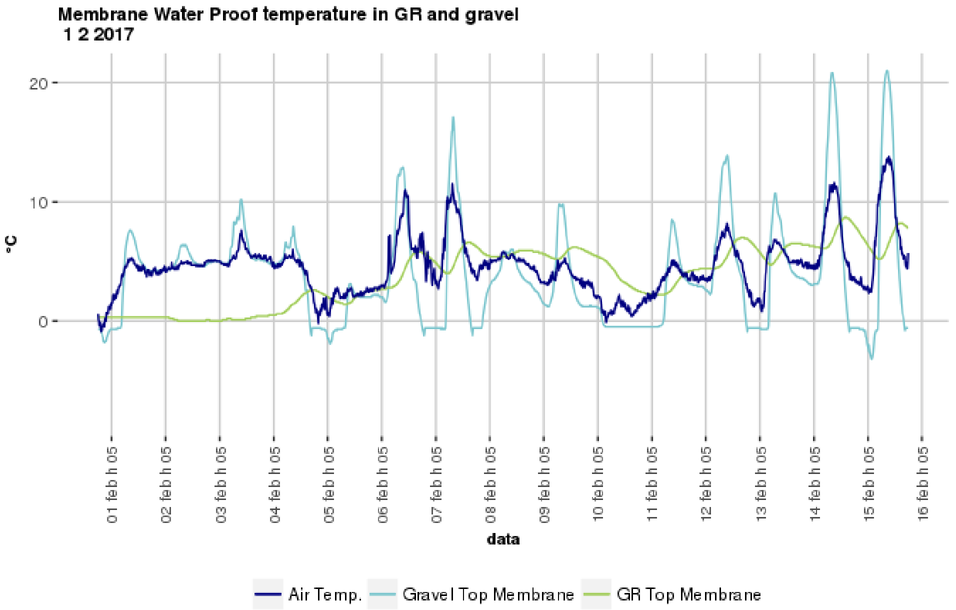


Figure 46   Winter membrane temperatures: extract of a ten day period in February 2017

Looking at one day sample (FIG)   the maximum is reached at about 2 PM, as air temperatures do. The almost flat line of temperature under Green roof membrane reach the maximum late in the afternoon..

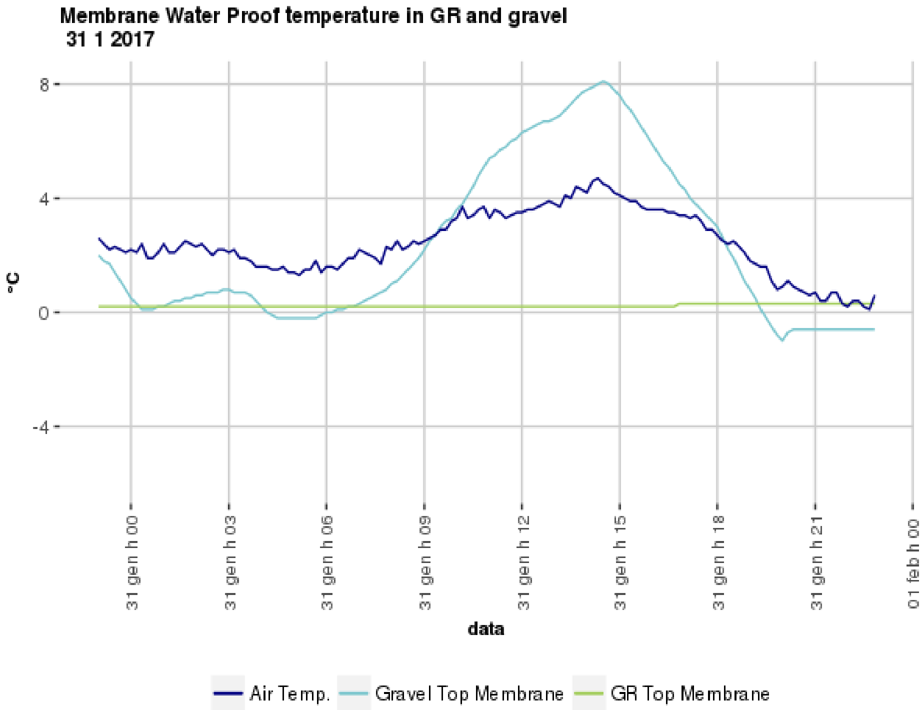


Figure 47   One day sample of Membrane temperatures in winter

Heat Flux

Heat flux follows the membrane temperature trends. Heat gain or loss has higher value in reference roof than in the green roof. Maximun gains are in the region of 7 W m-2 at about 2 PM , while on the green roof 1 W m-2 is gained with a delayed time of 6 hours. The maximum loss of 3 W m-2 occurs on the reference roof at 6 AM, while on the green roof less than 1 W m-2 is lost at 8 AM.

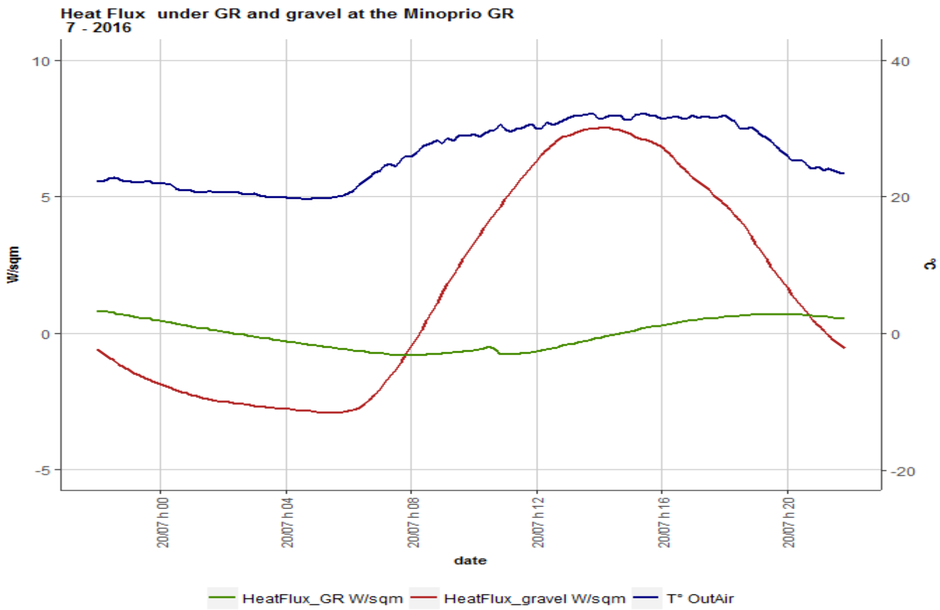


Figure 48 One day sample of heat loss in summer

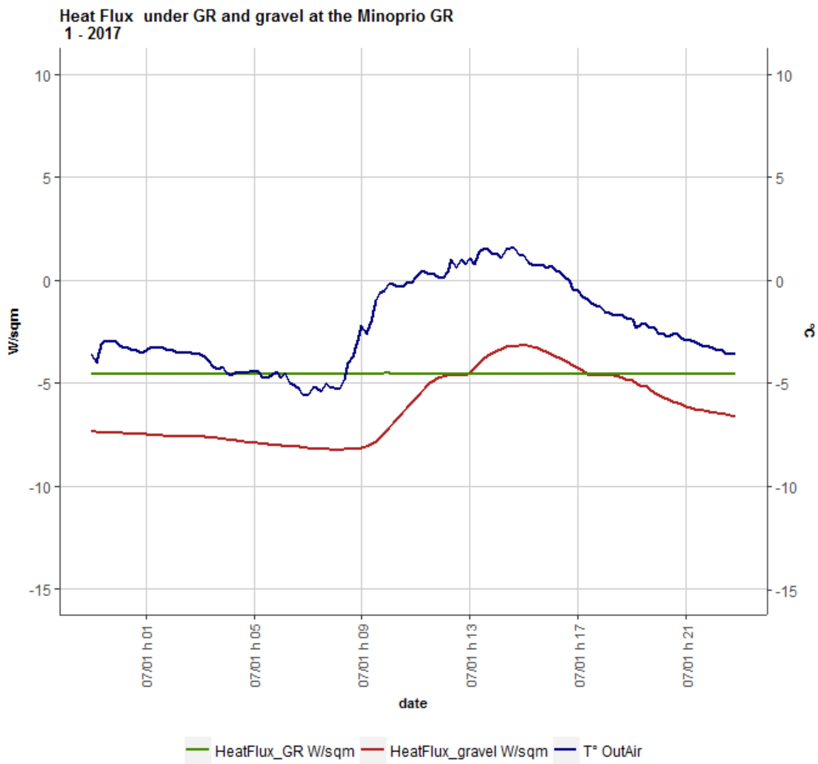


Figure 49 One day sample of heat loss in winter

In winter the heat lose is costant on the green roof. The loss on the reference roof is 3 W m-2 higher during the day except for early afternoon hours when it has a peak of 1-2 W m-2 less than the green roof. In the sample day shown in Figure 49, the minor loss endures for only 4 hours.

Energy balance

By aggregating the data of daily heat flux, a monthly balance may be drawn. In FIG the balance has been plotted for the Minoprio green roof and reference roof.
The bar plot shows that the green roof does not gain heat neither in winter nor in summer, whilst the reference roof gains heat in summer.
From October to January the loss of heat is greater on the reference roof, but from February to May it is higher on green roof. This behaviour is likely to be due to the plant growth and its consequent high evapotranspiration. This pattern has been reported also for other green roofs. The balance is not related to inner ceiling roof (reference roof= gray, green roof = lightblue) because the overall balance must take into account the othe rsurface gain losses. Moreover the high insulation coefficient of new roof allow very low differences.

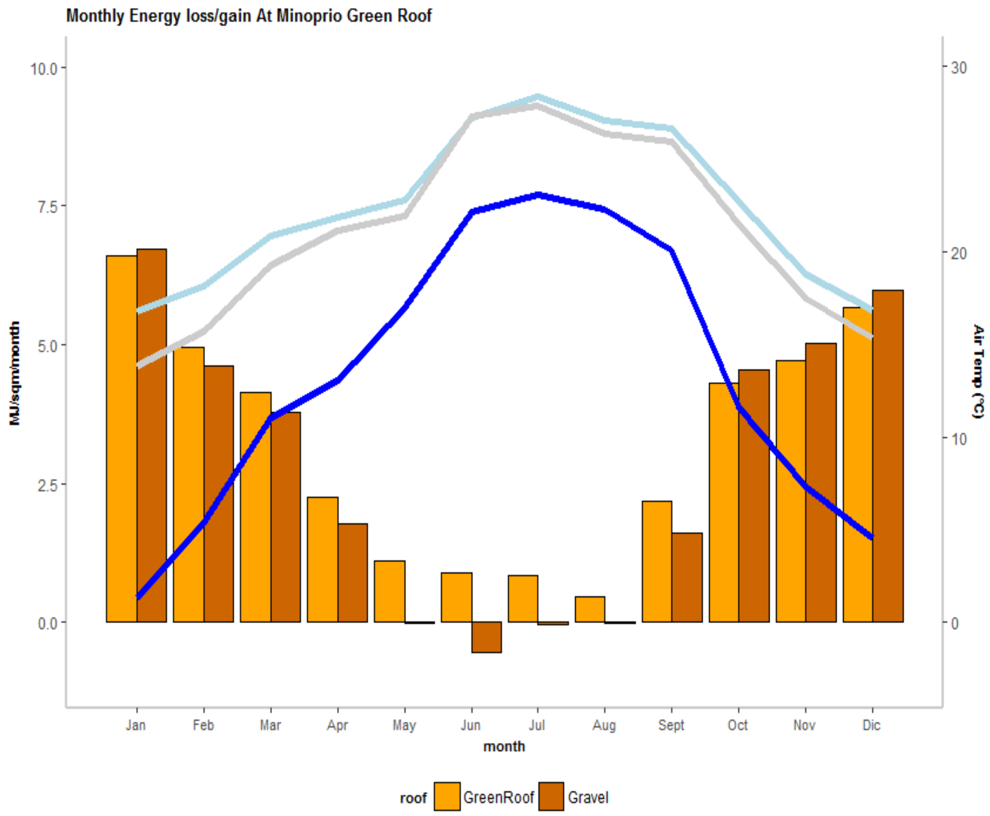


Figure 50 Monthly energy balance at Minoprio.

Politnergy balance at Politecnico

At Politecnico the heat flux values as measured by the sensor on the ceiling was plotted. The amount of energy lost in February at Politecnico is about the same as in Minorpio, but in March it is enhanced. Of particular relevant is the significant gain of energy that happens in June. This is thought to be due to the limited insulation of the roof which was constructed some forty years ago.

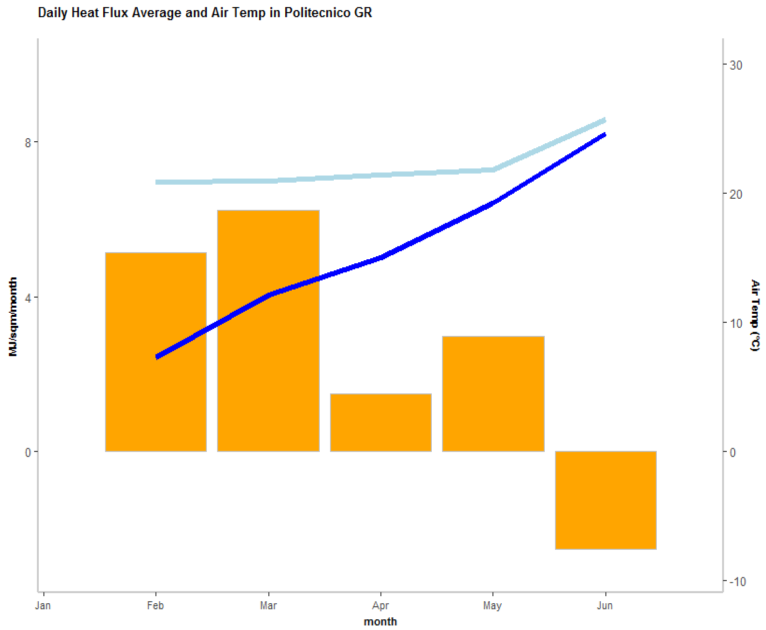


Figure 51   Monthly energy balance at Politecnico

4 Summary and Conclusions

4.1 Faculty for the Built Environment, Malta

Phase 2 - To investigate certain parameters that may affect the performance of green roofs.

The aim of this research was to investigate the effectiveness of green roofs in terms of their potential thermal performance and to provide objective data to illustrate the scope of any effectiveness.
An extensive appraisal of existing research was carried out as its first objective. The second objective was to investigate certain parameters that may affect the performance of green roofs. These were identified, measured and analysed by utilising six x $1m^2$ test trays. During the second phase of the study, the thermal performance of an actual green roof was investigated and compared with the performance of an adjacent conventional, concrete slab roof, thus satisfying the third objective. The purpose was to quantify the thermal performance improvements, particularly in terms of the green roof's ability to provide cooling during the hot Maltese summer months.

Six Test Trays were set up and investigations devised to answer the following questions:

1. What difference does the depth of substrate make to the thermal insulation performance of a green roof?
2. Does increased moisture improve the thermal insulation performance of a green roof?
3. Do plants make a difference to the thermal insulation performance of a green roof?
4. Does the morphology of a plant make a difference to the thermal insulation performance of a green roof?
5. Does increased moisture affect the degree absorption of solar heat at the surface of a green roof?
6. Does the morphology of a plant affect the degree absorption of solar heat at the surface of a green roof?

Test Tray Investigation

Question 1, investigated the effect of substrate depth on thermal performance. Three test trays were set up; one filled with growing media to a depth of 200mm; the second tray was half filled and the third left empty as a control. It was shown that the temperature measured beneath the empty tray fluctuated by as much as 47.8°C within 24 hours. The diurnal temperature fluctuation of the filled Tray was much as expected at 4.3°C, a reduction of heat gain of 91% compared to the empty control tray. In terms of the half-filled tray the diurnal temperature range was more than the filled tray but still considerably lower at 11.8°C than the heat gain of the empty tray. The percentage difference in heat loss being 75%. These results show that the substrate does have a considerable effect on reducing heat gain. However, halving the depth does not halve the heat gain. Therefore, in practical terms, the thinner depth of 100mm does effect a good reduction in heat gain at 75% and this is generally the depth utilised in extensive roof gardens. And where there are concerns about weight loading

on a roof structure then this depth would be adequate. Nevertheless the greater substrate depth would be preferred in an intensive green roof set up as it broadens the diversity of plants that can be used and increases plant survival in hot conditions (Farrell, et al., 2012).
The role that moisture plays in the effectiveness of the performance of green roofs was posed by Question 2. Two test trays were filled to a depth of 200mm. One tray was irrigated and the other left dry. It was found that the irrigated tray performed better in reducing heat gain by 40% through the substrate when compared to the non-irrigated tray. It was assumed that the irrigated tray absorbed solar energy in the process of evaporating water from the surface thus cooling the structure.
Question 3 asked whether the inclusion of plants affected the cooling effect on a green roof. Three test trays were selected. All had a depth of 200mm of planting medium and all were irrigated to the same level. One tray was un-planted and of the other two, one was planted with Phlomis fruticosa, an upright plant with leaves held above the planting media and the other tray was planted with the ground covering succulent, Sedum sediforme. It was shown that Sedum sediforme reduced the average, diurnal temperature by 14% when compared with the un-planted test tray. The performance of the tray planted with Phlomis fruticosa was not so effective in reducing the heat gain within the tray and this could be due to the greater coverage of the growing media by the Sedum plants.
In terms of Question 4, it does seem that the morphology of the plants selected does have an effect on performance, however, further investigations of the effects of a range of plants would be useful. Question 5 set out to find whether the moisture content of the planting media affects the cooling performance of the planting medium layer. It was shown that the irrigated tray had a diurnal range of 4.4ºC with a peak temperature of 32.4ºC compared to the higher temperatures of the non-irrigated tray which had a peak temperature of 34.2ºC and a range of 6.4ºC. This represented a 31% reduction of heat gain over the diurnal range.
Question 6 sought to investigate the effect of plants with differing morphology on the solar heat gains at the surface of the planting media within the test trays. As with the investigation into the effect of different plants on the heat flow through the planting media (Question 4) the results showed that Sedum sediform performed better in reducing the solar heat gained at the surface.

In conclusion it can be said that the first phase of the research showed that:

- The depth of the planting media does improve the thermal insulation performance of the green roof and that a relatively shallow depth of 100mm is effective.
- Increasing the moisture content of the planting medium through regular irrigation improves the thermal performance of the green roof.
- Adding plants to a green roof can improve its thermal performance although the morphology of the plants selected is important.

Green Roof investigation Phase 3

The aim of this phase of the research project was to quantify the thermal performance improvements that emanated from the installation of a green roof by comparing the thermal performance of the green roof with that of the adjacent conventional roof. During the heating month of March it was seen that the temperature as measured at the surface of the soffit beneath the green roof was higher than that of the soffit under the conventional roof. The greatest difference was recorded at 1.27ºC on the 4th of March 2016. The presence of the green roof provided greater thermal insulation and thus would reduce the need for mechanical heating of the occupied spaces below. As the external air temperature rose above the region of 16ºC towards the end of the month of March, then the green roof reversed its influence and maintained the temperature, as measured beneath the soffit, at a cooler temperature compared to the readings of the soffit beneath the conventional roof.

Experimental Limitations

It has been shown by other studies, that green roofs are more effective in reducing heat gains in the cooling months than heat loss in winter (Liu, 2003). This is an important consideration in Malta which experiences a prolonged cooling period. Therefore in terms of reducing heat gains in the cooling months it was shown that the addition of the green roof consistently reduced the temperature recorded beneath the soffit as compared to beneath the conventional roof. However, the maximum reduction of heat gain was in the region of 1.32^{o}C. This represents a 5.8% reduction in heat gain in cooling months compared to the conventional roof. Although this signifies a potential positive result in terms of saving of energy via the reduction of the use of mechanical means of cooling space, it does seem very modest when compared to other similar studies. For instance, researchers at the Carnegie Mellon University in Pittsburgh, USA recorded a 75% reduction in heat gain in the cooling months (Becker & Wang, 2011). Similar research carried out in Austin, Texas, which experiences a comparable sub-tropical climate to that of Malta, found that the inside air temperatures as measured beneath the green roof was 18^{o}C cooler than under the conventional roof (Simmons M. T., 2008). This latter value is higher by a magnitude of greater than x10 compared to the result experience at the Faculty for the Built Environment, University of Malta.

Two factors could account for this rather modest result:
Firstly, the structure of the conventional concrete slab which is continuous under the green roof was unknown as architectural plans of the building were not available. It has a measured thickness of 550mm (Typically roof thicknesses range from 150mm to300mm). It was decided to take a core sample of the Roof slab in question in order to discover its internal composition Figure 4-1 below is a drawing of what was discovered. It reveals 50mm layer expanded polystyrene (Jablo) beneath an 80mm layer of crushed limestone (Torba). Both of these elements but particularly the polystyrene and known for their insulator character or high thermal resistance (R-value). An experimental set up was devised to measure the actual individual layers of the core. The sample core was inserted into a cylinder of the same diameter cut into a block of polystyrene. A heat source of known output (2.6w) was suspended within the void above the core. Thermocouples were placed at each layer intersection and two heat flux sensors were placed at the top of the core sample and the other at its base. The experimental set-up is illustrated in Figure 52 below

The results of the investigation are shown graphically below in Figure 53 below. The horizontal axis labels stand for the following:

- T-1 = Top of core on day one (26/05/17 – average over the day)
- B-1 = Base of core on day one (26/05/17 - average)
- T- +19 = Top of core 19 days later (14/06/17 – average)
- B - +19 = Base of core 19 days later (14/06/17 – average)

The investigation was allowed to run for 19 consecutive days from 26/05/17 until 14/06/17. This was to allow the heat flux values to stabilise for a period of three days. The graph shows that the top of the core maintained an energy flow value of around 5.9mV throughout. This is to be expected as the heat source was left on at a steady energy output. However, the heat flux value transmitted through the core sample and measured at the base only increased by 0.12mV. This result confirms the initial speculation that the thermal resistance of the roof slab was significant and that this was likely to have resulted in a 'dampening' effect in terms of the thermal performance of the Maltese green roof compared to the results gained from other studies.

Experimental set-up (a) each element is carefully packed into the cylinder cut into the polystyrene block to replicate the composition of the actual roof slab. (b) layer of crushed limestone (Torba) with thermocouple in place above. (c) Completed and sealed unit, heating unit is beneath the top block of polystyrene. (d) data collection equipment

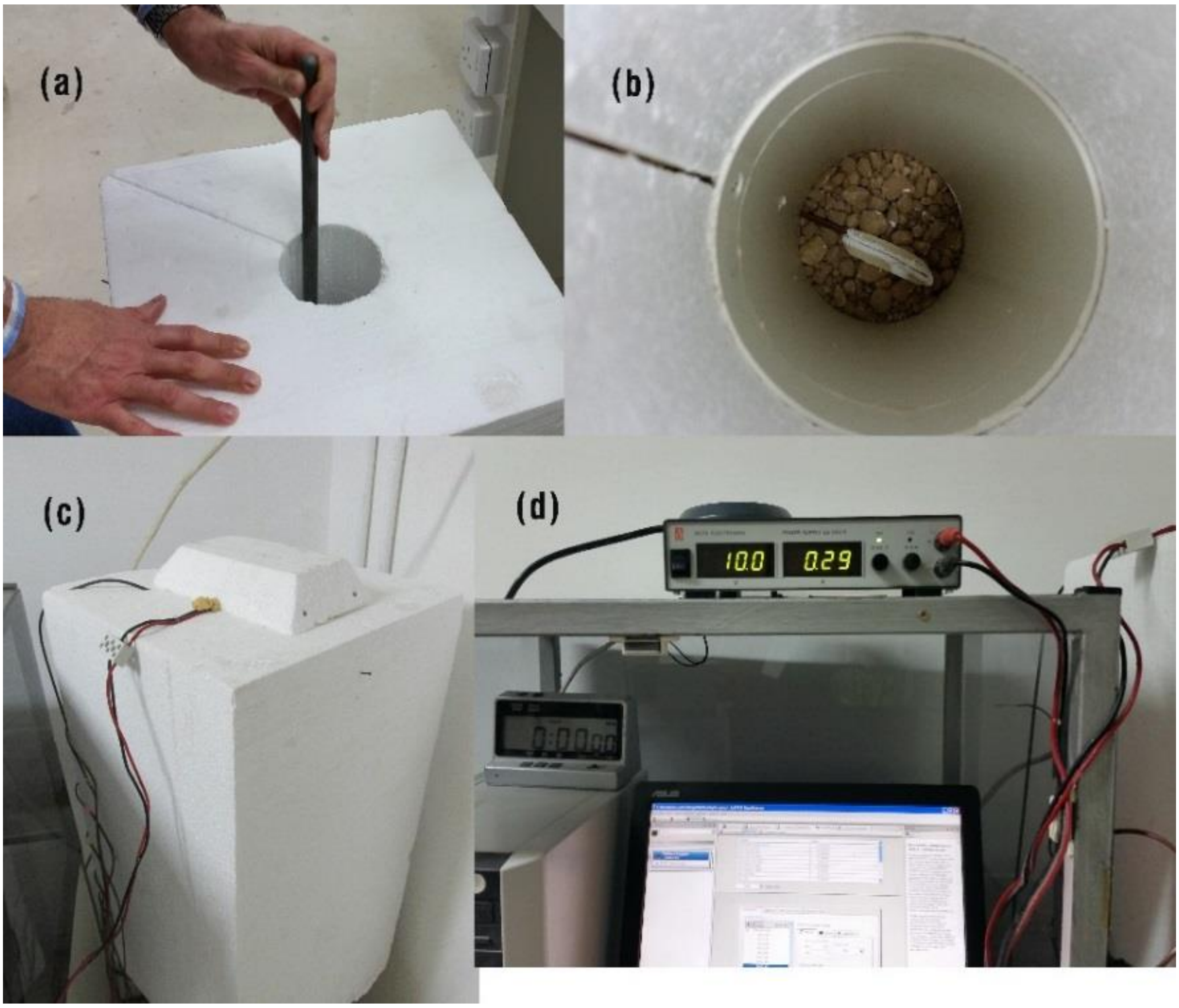


Figure 52 Experimental set-up to assess the thermal resistance of the various elements of the core taken through the roof slab above the Faculty of the Built Environment.

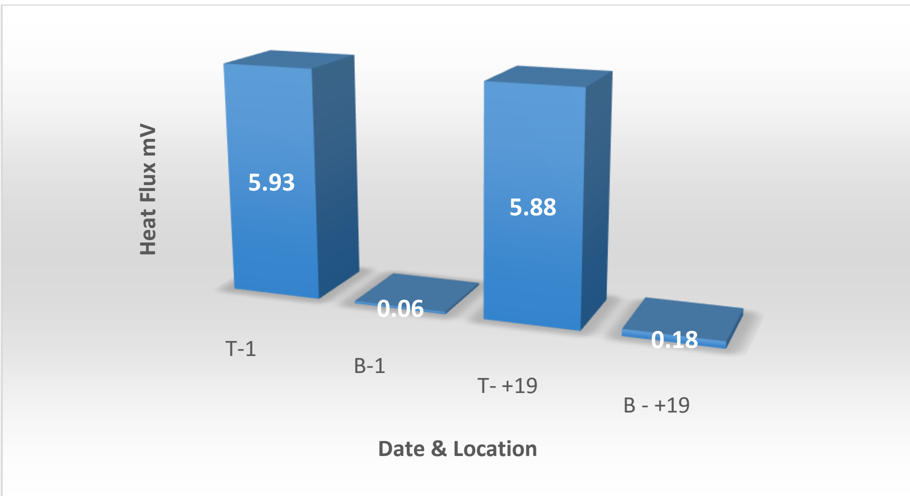


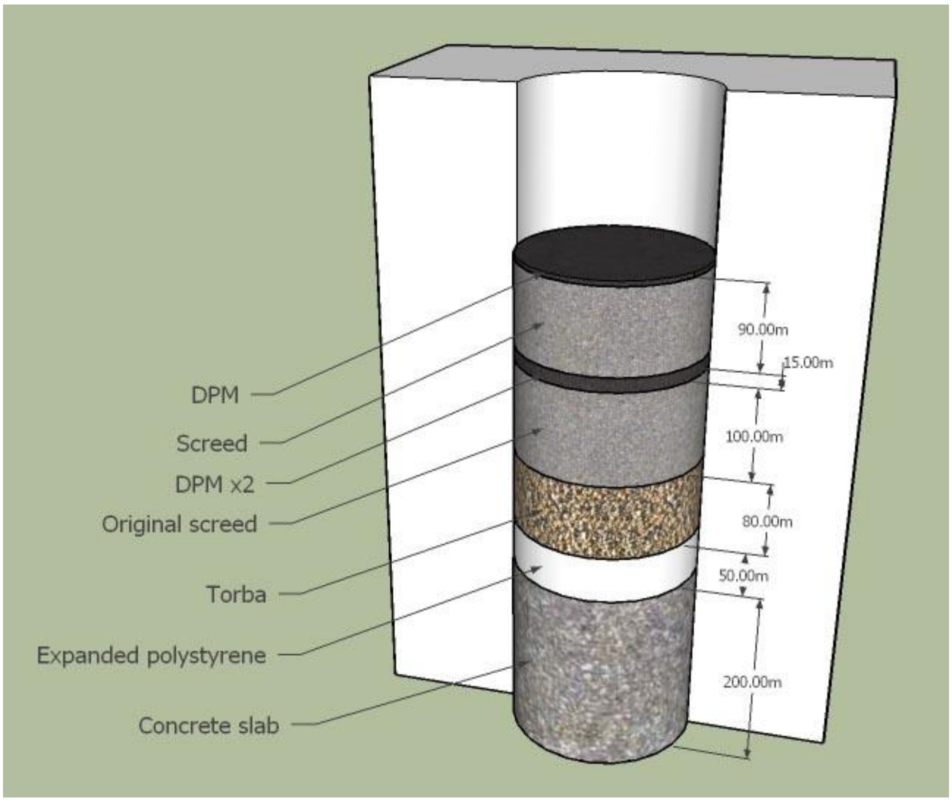
Figure 53 Heat Flux values for the core sample

From the acquired readings, it was possible to calculate that the core sample had a resistance (R.) value of 3.3 giving a corresponding 'U' value of 0.30. (Figure 54 below). This can be compared to a more typical roof slab section as shown in Figure 55 which has a much reduced thickness of 270mm and without a polystyrene layer. Its corresponding 'U' value was calculated at 2.3. The benefit of installing a green roof on this typical roof construction would obviously result in substantially greater insulator benefits.

Estimation of energy saved

Due to the many variables involved in the construction of the host roof and the green roof, it is difficult to predict how much energy and thereby costs would be saved by installing a green roof. However, and attempt has been made to predict how much energy, in percentage terms, could be saved. This figure is thought to be in the region of a 49% saving of energy use. The calculations of how this figure was arrived at is included in Appendix C.

Figure 54 Diagrammatic interpretation of the slab core of the Faculty of the Built Environment / 'U' value = 0.30



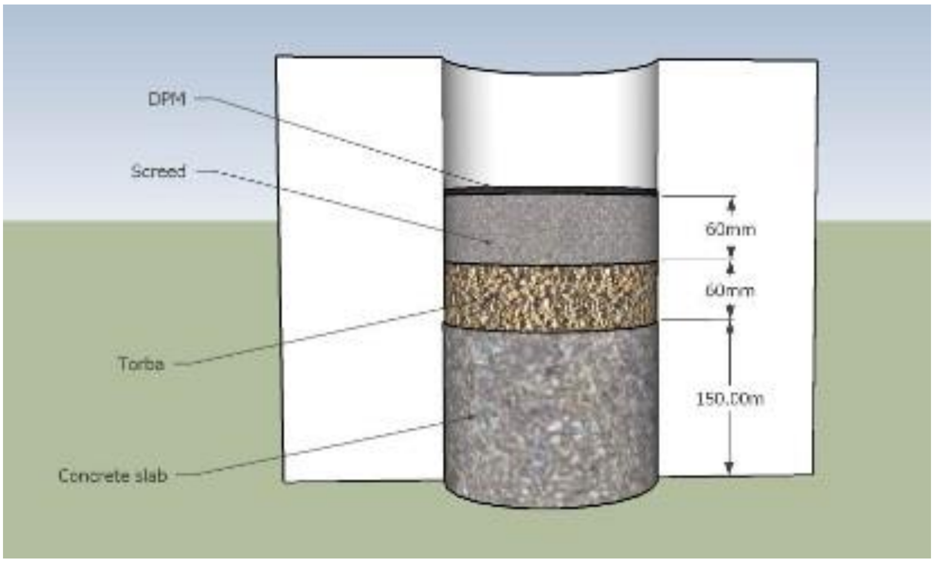


Figure 55 Traditional slab roof / 'U' value = 2.3

The second factor to take into consideration is that the thermocouple sensors beneath the conventional roof and green roof were located approximately 4 meters apart. This occurred due to constraints imposed by the availability of equipment and the site. It is possible that lateral conduction of heat through the concrete slab could have had a moderating effect on the readings taken under the green roof. It would perhaps improve the results if the sensors were set much further apart or located on different buildings as happened at the Carnegie Mellon University (Becker & Wang, 2011). Alternatively, a thermal barrier or 'median barrier' could be installed as was the case in a similar study carried out at the Institute for Research in Construction in Ontario, Canada (Liu, 2003).

Nevertheless, the installation of the green roof had a marked influence on the temperature range of the roof membrane. Even in the relatively cool conditions of early March the daily temperature amplitude of the green roof had a range of 0.58^{o} C while the amplitude of the conventional roof was 22.86^{o} C. This represented a 97% reduction of heat gain under the green roof. In protecting the membrane from such large temperature amplitudes it is likely that green roofs will greatly extend the life span of roof membranes.

Estimation of the potential energy that could be saved

Due to the many variables involved in the construction of the host roof and the green roof, it is difficult to predict how much energy and thereby costs would be saved by installing a green roof. However, and attempt has been made to predict how much energy, in percentage terms, could be saved if a green roof were to be installed on a conventional roof in Malta. This figure is thought to be in the region of a 48% saving of energy use. The method of calculation by which this figure was arrived at is included in Appendix C.

Project Objectives.

This study has accomplished what it set out to do which was firstly, to investigate the influence that the varying of certain parameters of the green roof structure affect its thermal performance. Secondly, the investigation of the thermal performance of the actual green roof located above the Faculty for the Built Environment at the University of Malta has shown that green roofs have the potential to reduce heat loss in the heating months of a Maltese winter but more importantly is their ability to reduce heat gain in the cooling months of Malta which span from April to

September. This reduction of summer heat gain could mean that mechanical cooling of occupied spaces could be substantially reduced thus saving energy.
It has been suggested that green roofs would be of more value retrofitted onto older properties as more modern buildings may possibly have higher levels of thermal insulation specified in more recent building regulations (Castleton, et al., 2010). Buildings with thermal insulation included in their roof structure would still benefit from the additional thermal resistance provided by a green roof. This would be in addition to the other economic, environmental and social benefits the Green roofs have been shown to provide. The same cannot be said of the more traditional engineered methods of insulating a building. The promotion of green roofs in Malta could make a significant contribution to the Government's commitment to reduce the use of fossil fuels and thereby help to reduce the contribution to Global Warming.

4.2 Conclusions – Foundazione Minoprio Italy

The thermal performance of the green roof located at the Fondazione Minoprio, Italy was characterised by a modest loss of heat energy in the winter months compared to the adjacent conventional gravel roof. In early spring there was a gradual trend to a reversal from the prevention of heat loss to the prevention of heat gain. This reversal trend is similar to that recorded in Malta.

Figure 54 Green Roof and weather station at the Foundazione Minoprio, Italy

In the summer cooling months, the green roof continues to prevent the gain of solar heat within the building envelope while the reference roof shows a gain in internal heat accumulation. The difference of energy loss/gain is indeed not huge as was also the case in Malta. However, in Italy, this is thought to be due to the modern technologies of roof construction that needs to respect very low heat transmittance U-values as specified in local building standards and regulations. In Malta, as has been explained above, the high thermal resistance was due to the thickened of the roof slab and to internal layers of insulator material. The additional green roof constructed on the Politecnico building in Milan demonstrates a pattern similar to the Minoprio one, that is, during summer months there is a similar reduction in heat gain.

Regarding the cooling season (June to August) the gain in balance is substantial in percentage. Despite this, the actual values measured do not account for great saving in terms of energy. In the winter the values of the balance are much higher, but the percentage saving is in favour of green roof by a margin of only 1%.

These limited values are thought to be due to the new thermal transmittance coefficient requested by current regulations concerning insulation.

4.3 Further Studies

Research of green roofs is still in its infancy in the Mediterranean region and there is much scope for further areas of investigation. The selection of two species of plants in the Maltese study was limited and there would be merit in looking at the effect of a wider selection of plants in terms of their effect on the thermal efficiency of green roofs. The use of computer simulation has been mentioned (Decruz, et al., 2015) and this would be a very interesting and valuable field of research that could be used to predict thermal performance in a variety of scenarios. The simulation if linked into a whole building assessment could also be used to calculate the potential energy savings resulting from the thermal performance of green roofs in various situations.

Apart from the thermal performance of green roofs there is much scope in investigating other aspects of green roof that would be beneficial to the environment. For instance, the implications of green roofs on reduced water runoff and the delay in discharge could be valuable research that would have practical benefits to Malta where local flooding is a particular problem. The aesthetic aspect of green roofs and the influence this could have on people's wellbeing would be another valuable sphere of study.

Both the Foundazione Minoprio in Italy and the Faculty for the Built Environment at the University of Malta have excellent facilities for further studies into the performance of green roofs being national benefactors of the European Union's Life+MedGreenRoof Project funding (2014 -2017). It is hoped that future faculty staff and students will be motivated to add to the body of accumulating knowledge relating to the potential benefits of green roofs, particularly in the context of the sustainable future of the Mediterranean region.

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Appendix A Equipment Specifications

A.1 Data Loggers

A.1.1 Model E-Log - Environmental Data Logger (Main Data Logger used on the green roof)

Image

Manufacturer's Description

E-Log has been explicitly designed for environmental applications. It features specific inputs and calculations for environmental sensors while maintaining an all-time-low power consumption. E-LOG stores data sampled from connected sensors and supports a wide range of communication protocols. Rugged and durable, E-LOG ensures prolonged data-logging in even the most severe environments, while the 16-bit design of the A/D converter ensures data accuracy and reliability of measurements in meteorological and hydrological applications, for air quality and outdoor environmental monitoring.

Software

LSI-LASTEM 3DOM Software for data logger setup, diagnostics and data downloading used for M-Log, E-Log and R-Log MASTER packages.

Specification

- N.8/16 analog inputs, 4 digital inputs, n.1 RS232 input;
- Inputs extension using MASTER/SLAVE units;
- Available with built-in ZigBee radio;
- Very low power consumption (< 4 mW);
- N.99 channels for acquisition or calculation;
- 2 MB Flash data memory;
- LSI-LASTEM, Modbus RTU, TTY communication protocols;
- Spontaneous data transmission in ASCII format by TCP protocol;
- N.2 RS232 serial ports;
- Built-in calculation library for derived quantities;
- Built-in mathematical calculations library;
- Outputs actuation over programmable events to activate external devices;
- Sampling rate 1 sec. to 12 hrs;
- Elaboration time-base 1 sec. to 24 hrs;
- PC connection via RS232/radio/modem PSTN/GSM/GPRS/Ethernet;
- Display and keyboard;
- Compatibility with CommNET, GIDAS and XPanel programs.

A.1.2. Model R-Log - Radio Data Logger (used as a 'Slave' unit on the main green roof)

Image

Manufacturer's Description

R-Log data logger is a line of devices for environmental measurements in indoor and outdoor applications; it gives the utmost flexibility in terms of multiple measurement design. It can manage a large variety of sensors and, thanks to its radio technology, it's also a multi-position measurement system. The two features make the system extremely flexible in terms of typology, position and number of managed sensors.

Specification

- Portable use or fix installations system;
- Multi-position measuring system using wireless communication from MASTER to SLAVE units;
- N.4 analog inputs, n.1 digital inputs;
- Inputs extension using MASTER/SLAVE units by radio;
- Wireless connection to Radio sensors;
- ZigBee radio 2.4 GHz frequency;
- N.50 channels for acquisition or calculation;
- 2 MB flash data memory;
- Derived quantities calculation;
- Math calculations;
- Outputs actuation over programmable events to activate external devices;
- Sampling rate 1 sec. to 12 hrs;
- Elaboration rate 1 sec.. to 24 hrs;
- PC connection via RS232/radio/modem PSTN/GSM/GPRS/Ethernet
- Display and keyboard;
- Compatibility with CommNET, GIDAS and XPanel programs.

A.1.3. National Instruments NI 9213 Thermocouple Data Logger (used in conjunction with the Test Trays)

Image

Manufacturer's Description

The NI 9213 is a high-density thermocouple module for CompactDAQ and CompactRIO chassis. Designed for higher-channel-count systems, the NI 9213 adds thermocouples to mixed-signal test systems without taking up too many slots.

Specifications16 TC, ±78 mV, 24 Bit, 75 S/s Aggregate

• Spring-terminal connectivity

• 50 Hz/60 Hz noise rejection

• Up to 0.02 °C measurement sensitivity

• 250 Vrms, CAT II, channel-to-earth isolation

A.2. Heat and Moisture Sensors

A.2.1 Thermocouple Type ‘T’ (used with the test trays)

Image

Description

The thermocouples that were used in the test tray investigations were the Copper-Constantan (Type ‘T’) which provide accurate readings.

Specification

Attribute Type	**Attribute Value**
Thermocouple Type	T
Number of Cores	2
Core Strands	7/0.2mm
Temperature Rating	-10 to 105°C
Reel length	25m
Screened	No
Insulation Material	PVC
Colour	Brown

A.2.2 Thermocouple – Pt100 1/3 DIN B (Class AA) ‘Flat sensor’ (used for soffit and membrane readings)

Image

Manufacturer’s Description

Plate-made sensor for surface temperature measurements. Its compact dimensions facilitate installation even in small spaces. It can be easily fixed using silicon, adhesive band or thermoconductive paste.

Specification

Temperature	
Principle	Pt100 1/3 DIN B (Class AA)
Measurement range	-50÷70°C/td>
Accuracy	0,15°C (@0°C)
Output	Pt100 DIN-IEC 751 table (EN 6075)
Resolution	0,01°C (M/R/E-Log)
Response time (T90 air)	35 sec
General information	
Dimensions	30 x 20 mm. Thickness 2,5 mm
Power consumption	None
Operative temperature	-40÷80°C
Input type on E/M/R-Log	Analog

A.2.3. Air Temperature Sensor (used to record air temperature in space beneath the soffit)

Manufacturer's Description

DMA672.1 air temperature sensor for indoor use and, coupled with a radiant screen, in meteorological applications; this sensor is ideal for virtually any kind of environmental application. A 4-wire, Pt100 1/3 DIN B sensing element guarantees very good accuracy over an extended temperature range.

Specification

Temperature	
Sensitive element	Pt100 1/3 DIN B (Class AA)
Measuring range	-50÷70°C
Accuracy	0,10°C (@0°C)
Output	Pt100 DIN-IEC 751 table (EN 60751)
Resolution	0,01°C (M/R/E-Log)
Response time (T90)	30 s. 1 min. with filter
General	
Protection	IP54
Power consumption	n/d
Operative temperature	-40÷80°C
Cable	L = 5 m
Input type on X/E/M/R-Log	Analog

A.2.4. Temperature and Moisture Sensor (used to record air temperature and moisture of planting media in green roof and test trays)

Image

Manufacturer's Description

DQA340 is the ideal solution for the measurement of volumetric moisture in soils and other porous materials. The sensor is based on TDR technology (Time Domain Reflectometry), ensuring good accuracy even in very wet soils, and without special calibration for mineral soils. Using its rods, the sensor can be inserted in the material for 11 cm. It measures both soil moisture (0-100% range) and temperature.

Specification

Soil moisture	
Principle	TDR (Time domain reflectometry)
Measurement range	0÷100% volumetric moisture
Accuracy	0÷40%: ± 1%, 40÷70%: ± 2%
Temperature	
Principple	Pt100 1/2 DIN B
Accuracy	± 0,2°C
General Information	
Power supply	6÷24 Vdc
Power consumption	Sleep: 5 mA; Measuring: 120 mA
Cable	L = 5 m
Output	2x0÷1 V

A.2.5. Soil Temperature Sensor (used to record temperature at surface of planting media in green roof)

Image

Manufacturer's Description

Soil temperature sensors DLA400 is used for temperature measurement on soil surface or in the first 50 cm of depth. Pickets assure sensor stability when deeply inserted in the ground or in case of surface measurement. A ring is used to position the sensor at the required depth. A radiant screen protects the rod from the direct solar radiation. DLE041 is made of a tightly waterproof shank and can be completely buried in the soil at the required depth.

Specification

Use - On surface or in the first 50 cm deep soil Fill-in inside the soil

Common features - Soil temperature Principle Pt100 1/2 DIN B (Class AA)

Measuring range- Depending by the data acquisition system

Accuracy - 0,15°C (0°C) Output Pt100 DIN-IEC 751 table (EN 60751)

Cable L = 10 m

Housing - Stainless steel AISI 304

Operative temperature -20÷±+70°C

Accessories - Order numb. DLA403 Radiant screen for DLA400 DLA404 Depth setting ring for DLA400 DLA401 Picket L = 50 mm for DPA400 DLA402 Connection rod for DPA400

A.3. Albedometer

A.3.1 SRA01 Albedometer

Image

Manufacturer's Description

SRA01 albedometer is an instrument that measures global and reflected solar radiation and the solar albedo, or solar reflectance. It is composed of two identical second class pyranometers with thermopile sensors, the upfacing one measuring global solar radiation, the downfacing one measuring reflected solar radiation. SRA01 complies with the latest ISO and WMO standards.

Specification

Measurand - hemispherical solar radiation and reflected solar radiation

Optional measurand - albedo or solar reflectance

Optional measurand - net solar radiation

Included sensors - 2 x identical ISO 9060 second class pyranometer

Mounting - ¾ inch NPS tube (not included)

Calibration uncertainty - < 1.8 % (k = 2)

Calibration traceability - to WRR

Measurement range - 0 to 2000 W/m^2

Spectral range - 285 to 3000 x 10^{-9} m

Sensitivity (nominal) - 15 x 10^{-6} V/(W/m^2)

Rated operating temperature range - -40 to +80 °C

Temperature response - < ± 3 % (-10 to +40 °C)

Standard cable length - 5 m (see options)

A.4. Thermal Camera

A.4.1 FLIR E60 Thermal Imaging Camera

Image

Manufacturer's Description

The FLIR E60 provides a safe, non-invasive and effective method for finding and diagnosing potential electrical, mechanical and industrial problems. Layered infrared (IR) and digital images give you exceptional insight into the unknown and unseen.

Specification

Detector Type	320 x 240 pixels
Temperature range	-4 to 1202°F (-20 to 650°C)
Thermal sensitivity (N.E.T.D)	<0.05°C at 30°C.
Picture-in-Picture (P-i-P)	Scalable P-i-P
MPEG 4 Video Recording	Yes
Video Camera w/Lamp & Laser	3.1MP/LED Lamp/Laser pointer
Digital Zoom	4X Continuous
Image annotation	Voice (60s)/Text Comments
Moveable Spot	3 Spotmeters
Area Box	3 Area Boxes (full image with min / max / avg)

Appendix B

Planting Medium Specifications

The planting medium used in the test trays and green roof was composed of a mix of both inorganic and organic elements. The inorganic elements were composed of crushed Lapillus and Pumice. These two inorganic minerals are derived from volcanic origins. These materials were selected as they do not include any of the clays and silts that form many ordinary 'soils.' Clays and silts could potentially block the filters and impede the underlying drainage system making up the green roof structure. The Lapillus and Pumice have the other advantage of being relatively light in weight due to their vesicular structure. This ensures an open, aerated composition to the planting medium which aids good drainage. The two crushed volcanic minerals were mixed with the organic coconut fibre, green waste, and Biochar as described below.

Surface view of the planting medium.

Inorganic Elements (crushed volcanic minerals)

Lapillus
Ø 5-10 mm
pH ≤ 8,5

Pumice
Ø 3-8 mm
pH ≤ 8,5

Organic Elements

Coconut fibre

Coconut fibre, or Coir is a natural fibre extracted from the husk of coconut and used in products such as floor mats, doormats, brushes, and mattresses. In horticulture, coir is a substitute for sphagnum moss because it is free of bacteria and fungal spores. Its hydroscopic properties provides a valuable source of retained water for use by the plants.

pH 4,5 - 7,5
electrical conductivity ≤ 50 mS/cm
(extraction in water 1:1,5) .

Green Compost

This is the product obtained by composting green waste materials. It provides valuable humus to the mix affording a range of plant essential elements. Composition is variable as it depends on the initial input of green waste. However, in the case of the green roof the green compost was specified to Italian Legislative Decree no. 75/2010.

Biochar

Biochar is charcoal used as a soil amendment. Like most charcoal, biochar is made from biomass, in this case wood pellets, burnt in the absence of oxygen (pyrolysis). It is used to improve soils as it enhances nutrient availability and also enables soils to retain nutrients and to some extent moisture for longer.

Percentage mix of planting media

The various components were mixed as per the following table to produce a homogeneous planting medium:

Component	% Volume
Pumice	30
Lapillo	35
Green compost	10
Coconut coir	10
Wood pellet biochar	15

Appendix C

Calculation of the percentage saving potentially resulting from the application of a green roof (200mmm deep) on a conventional Maltese, uninsulated roof slab.

The energy potentially saved by the application of a green roof is calculated firstly by calculating the Resistance (R) of each of the materials used in the green roof profile. This is achieved via the formula:

$$R = \frac{\Delta x1}{K1}$$

Where:

R = resistance
Δx1 = Thickness of material (m)
K1 = Conductivity of material (W/mK)

The thermal resistance (R) of each of the eight materials that make up the green roof are added together as follows:

$$R = \frac{1}{6} + \frac{\Delta x1}{K_1} + \frac{\Delta x2}{K_2} + \frac{\Delta x3}{K_3} ...+... \frac{\Delta x4}{K_4} + \frac{\Delta x5}{K_5} ...+... \frac{\Delta x6}{K_6} ...+.... \frac{\Delta x7}{K_7} + .. \frac{\Delta x8}{K_8} \quad \frac{1}{10}$$

Where:

$\frac{1}{6} + \frac{1}{10}$ are added to represent the convective heat transfer coefficients relating to the ambient air layers

1 = Screed layer
2 = Torba
3 = Concrete
4 = Growing media
5 = Filter layer
6 = Drainage layer
7 = Root barrier
8 = Damp proof layer

Inserting each value gives:

$$R = \frac{1}{6} + \frac{0.06}{0.41} + 0.06 / 0.8 + \frac{0.15}{2.3} ...+... \frac{0.2}{0.98} + \frac{0.003}{0.22} ...+... \frac{0.05}{0.92} ...+.... \frac{0.002}{0.19} + .. \frac{0.001}{0.19} \quad \frac{1}{10}$$

R = 0.82

The thermal transmittance or 'U' value for the green roof and conventional roof is the invers of the 'R' value therefor;

$$U = \frac{1}{R} = \frac{1}{0.82} = 1.2$$

Using the formula:

Q = U x A x $\underline{\Delta T}$
Q = energy flow in Watts

U = Thermal resistance

A = Area (m²)

ΔT = Temperature difference between inside and outside air

It is possible to calculate the energy flow in Watts through the conventional roof and the conventional roof plus the green roof:

Conventional Roof only

Q^{cr} = 2.3 x 1 x 10 = 23 watts

Conventional roof PLUS Green roof

Q^{cr+gr} = 1.2 x 1 x 10 = 12 watts

To find the % improvement in energy saving derived from the installation of the green roof we use the following formula:

$$100 \times \left[\frac{Q^{cr+gr} - Q^{cr}}{Q^{cr+gr}} \right] = \% = 100 \times \frac{[23 - 12]}{23} = \mathbf{48\%}$$

Therefore, in theory, adding a green roof to an uninsulated conventional Maltese roof could save in the region of 48% energy use. However, this calculation is very approximate as there are many variables present in a real situation that could modify this prediction.