Department of Mechanical Engineering

The Thermal and Rainwater Runoff Performance of an Extensive Green Roof System

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Abstract

This project addresses the thermal and rainwater runoff performance of extensive green roof systems. Of the three different types of green roof system (extensive, semi-intensive and intensive), extensive systems are the most easily established and provide a valid alternative to conventional roofing materials for most applications.

The objective of the project was to set up a test rig in order to assess the thermal performance of a commercially available extensive green roof system and to compare its rainwater runoff performance with that of a perspex sheet (to replicate a photovoltaic panel).

The results for the thermal performance of the green roof were obtained using Labview Signal Express. The results showed that the green roof provided a cooling effect for the room temperature beneath.

Results from the comparison in runoff between a green roof and a 'PV panel' suggest that green roofs have the capability to offset the 'poorer' runoff performance of PV panels. This provides an additional benefit to the cooling effect on PV efficiency.

It was concluded that the comparison of runoff between green roofs and PV panels provides an area for further research to draw more conclusive results.

Acknowledgements

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I would also like to thank Vinny Fryars at Bauder and Gordon Watson at TQR Ltd. for helping to provide the sedum blanket. Thanks also to my brother in law Colin Law for building the green roof rest rig.

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1 Introduction

1.1 Green Roof Definition

A green roof (also known as an eco-roof, nature roof, living roof or roof greening system) is a living, vegetative system that contains a substrate (growing media) and a vegetation layer at its outermost surface [1]. The design and construction between the roof structure and the growing media varies, but typically includes a geo-textile filter, drainage layer, root barrier and a waterproof membrane. Depending upon the vegetation layer, the growing media depth can vary from 20mm (for extensive systems utilising sedum mats) to 1500mm (for intensive systems containing large shrubs and trees).

1.2 Background

The concept of the green roof is not a new phenomena; with its basic functionality being utilised for several centuries. More recently, increasing urbanisation and the encroachment of ‘urban sprawl’ on to green belt areas has led to a ‘greying’ of the landscape and a reduction in amenable space. The increase in urban density in order to reduce this urban sprawl and the resulting loss in geographical identity - along with increasing environmental awareness - has increased the awareness of the advantages that green roofs can bring.

Green roof systems can provide a number of advantages, ranging from the associated environmental and ecological issues, through to the aesthetic impact of new and existing development. They can be used as a way of compensating for increased urban density – providing a visual and recreational escape from the ‘concrete jungles’ of urban landscapes. They can also allow rural buildings to blend in with their surroundings – an important benefit especially in areas of natural scenic beauty.

Many European countries have already acknowledged the related benefits of green roofs. In Germany, government legislation and fiscal incentive encourages their widespread use. This has resulted in over 80 million m^2 of green roofs, compared with only 1 million m^2 in the UK [2].

In the UK, there is as of yet no building regulations related specifically to green roofs, only to the general standards of roof construction. Green roofs can be constructed to meet these standards.

Therefore, further research in to the thermal and runoff performance of green roofs would be beneficial in integrating them into UK building regulations and standards.

1.3 History of Green Roofs

Although the term ‘green roof’ seems relatively modern, green roofs have in fact existed for several centuries in Northern Europe. Green roofs of turf construction were a common element found in vernacular styles of buildings in Northern Scotland, Iceland and other Scandinavian countries; and even at the turn of the 19th century over 50 per cent of inhabitants in Iceland still lived in turf-roofed buildings [3]. During the 19th century, the availability of cheap, reliable and low maintenance roofing materials brought to an end these traditional types of green roof systems.

Figure 1: *Traditional Viking House (Newfoundland)*

Figure 2: *18th Century Farm Building (Norway)*

Renewed interest in green roofs began to develop at the end of the 19th century in Germany, where they were promoted because of their fire retarding properties. In the early 20th century, architects such as Le Corbusier, Walter Gropius and Frank Lloyd Wright began to incorporate green roofs into their designs, several of which still exist as originally conceived [3].

The modern trend – associated with the green movement and sustainable design – was established in Germany in the 1960s; with Reinhard Bornkamm, a researcher at Berlins Free State University his first work on green roofs in 1961 [4]. Since then, green roofs have become increasingly popular in many countries, both as retrofit and in new construction applications, and many more research papers have been published.

2 Types of Green Roof

There are several different types of green roof: intensive, semi-intensive and extensive. The main difference between each of these types of green roof is the depth of the substrate and the vegetation used (with a thicker layer of substrate allowing for a greater variety of plants).

2.1 Intensive

Figure 3*: Intensive Green Roof (Beijing, China)* [5]

Intensive green roofs have a thick layer of soil, require irrigation, and have high water retention and fertile conditions for plants. The depth of substrate is generally between 150mm and 1500mm and the vegetation used ranges from herbaceous plants, shrubs and grasses to larger plants and, in some cases, even trees. It can be said that intensive green roofs are comparable to open spaces at ground level and can be made use of by building residents. As a result of the size of the plants used, the depth of substrate and its high water retention; the weight of an intensive green roof is significantly higher than that of conventional roofs. Therefore, substantial reinforcement of an existing roof structure or the inclusion of additional building structural support is required. Intensive green roofs also require a large amount of maintenance, regular irrigation and applications of fertiliser.

2.2 <u>Semi-Intensive</u>

Figure 4: *Semi-Intensive Green Roof (Merano, Italy)* [5]

Semi-intensive green roofs are constructed using various substrate depths (150mm to 500mm), thus combining elements of extensive and intensive green roofs. The vegetation used includes grasses, herbaceous plants, shrubs and coppices. Compared with intensive green roofs, the potential for using the roof for amenity purposes is generally limited. The loads imposed by semi-intensive green roofs are less than those of intensive green roofs and less irrigation and fertilisation are required.

2.3 Extensive

Figure 5: *Extensive Green Roof (Prague, Czech Republic)* [5]

Extensive green roofs have a thin layer of substrate (20mm to 200mm), require little or no irrigation, and have low water retention and nutrient poor conditions for plants. The thin growing medium can consist of recycled materials [6]. Extensive green roofs are less costly to install than intensive green roofs and are also cheaper to maintain. Generally they are planted with, or colonised by, mosses, succulents, wild flowers and grasses that are able to survive on the shallow low-nutrient substrates. Commercial systems in the UK generally use sedum as the principal plant species in the vegetation layer [3]. Sedums, which are low growing succulents, are favoured because they are drought and wind tolerant, from a dense covering and are aesthetically pleasing.

There are three main types of extensive green roof system available in the UK: sedum mats; substrate based roof and green/brown roofs for biodiversity.

2.31 Sedum Mats

A sedum mat is a base layer of Polyester, Hessian, or porous polythene onto which is laid 20mm of growing medium. This is sprinkled with sedum cuttings and these grow into the substrate to maturity. When installed the Sedum blanket (including the 20mm of growing medium) is rolled out onto either 50 – 70mm of growing medium (standard method) or directly onto a moisture retention blanket (ultra light weight method).

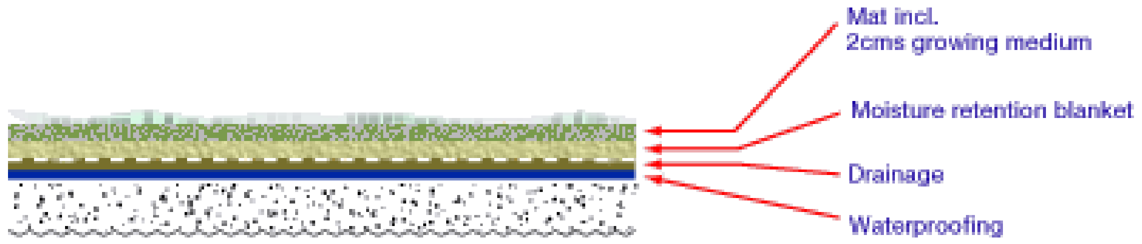


Figure 6: *Sedum Mat System (Ultra Light-weight)* [5]

2.32 Substrate Based Roof

70mm to 80mm of crushed recycled brick is placed on the green roof system and plug planted with sedums or hydro-seeded with other species. This type of green roof system contradicts the notion that green roofs are generally made of turf.

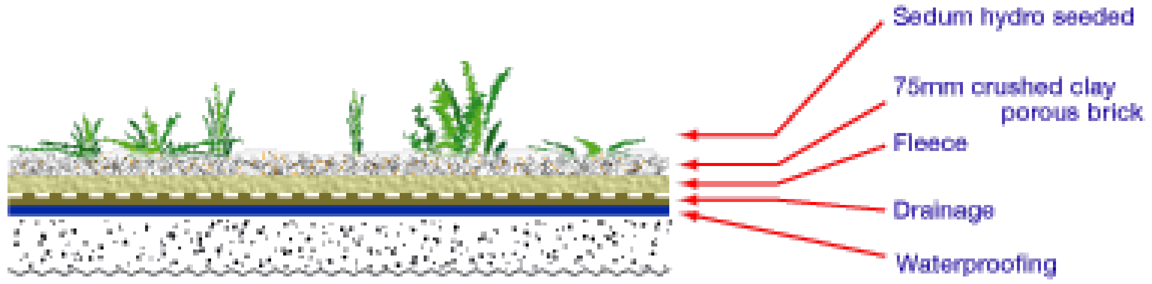


Figure 7: *Extensive Hydro Seeded* [5]

2.33 <u>Green/Brown Roofs for Biodiversity</u>

These are extensive green roofs that are designed to meet specific biodiversity targets. These generally require a bespoke designed system using locally characteristic substrates and plants. They can also make use of recycled aggregate from site and be left to colonise naturally or seeded with an annual wildflower mix or local seed source.

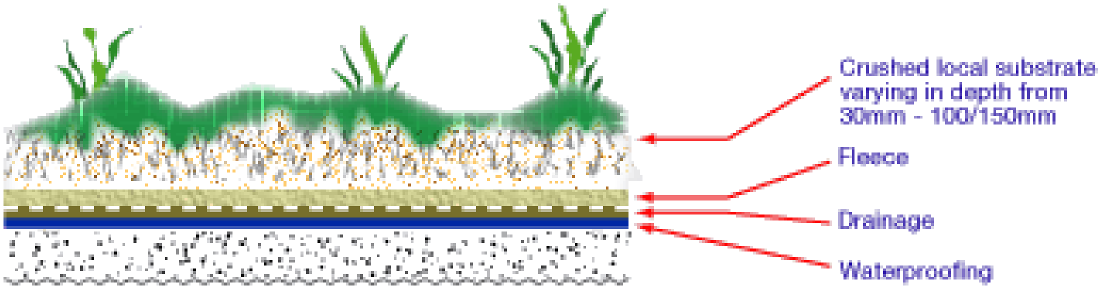


Figure 8: *Green Roof System for Biodiversity* [5]

The following table summarises the different types of Green Roof.

	Extensive Green Roof	**Semi-Intensive Green Roof**	**Intensive Green Roof**
Maintenance	Low	Periodically	High
Irrigation	No	Periodically	Regularly
Plant Communities	Moss, Sedum, Herbs and Grasses	Grass, Herbs and Shrubs	Lawn, Shrubs and Trees
Substrate Depth	20 – 200mm	150 – 500mm	150 – 1500mm
Weight	60 – 150 kg/m^2	120 – 200 kg/m^2	180 – 500 kg/m^2
Cost	Low	Middle	High
Use	Ecological Protection Layer	Designed Green Roof	Park/Garden

Table 1: *Summary of Green Roof Types* [2]

3 Construction of Green Roofs

The construction of green roofs is fairly well established and the various layers typically include:

1 **Vegetation Layer**

2 **Substrate**

3 **Geo-textile Filter**

4 **Drainage Layer**

5 **Root Barrier**

6 **Waterproof Layer**

7 **Roof Deck**

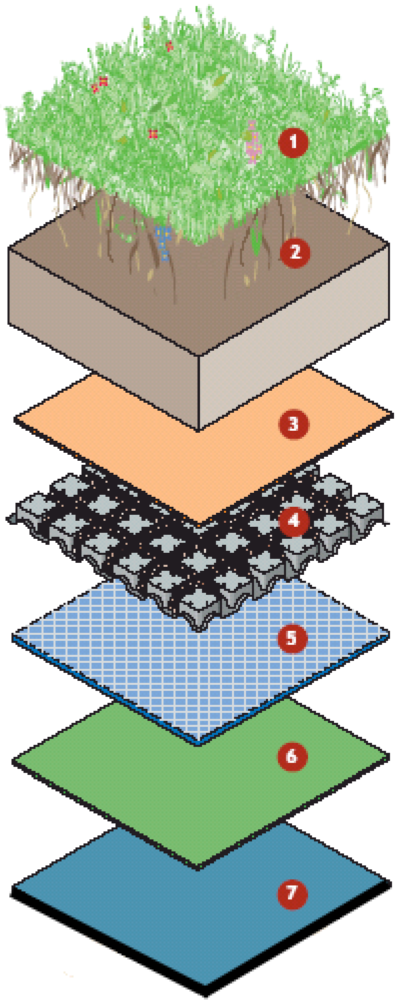


Figure 9: *Typical Green Roof Construction (with no insulation)*

The inclusion of insulation in green roof construction depends upon the type of roof being installed. Roofs are either pitched or flat. A pitched roof is defined as a roof with a slope greater than 10 degrees [7]. For the majority of pitched roofs the insulation is usually placed beneath the waterproof membrane.

A flat roof is defined as a roof with a slope of 10 degrees or less [7].

Flat roofs are normally categorized as one of the following three types, depending upon the location of the insulation and waterproofing membrane.

3.1 Warm Green Roof Construction

Insulation is placed between the exterior waterproof layer and the roof deck. A vapour barrier reduces condensation and no internal ventilation of the roof interior is required.

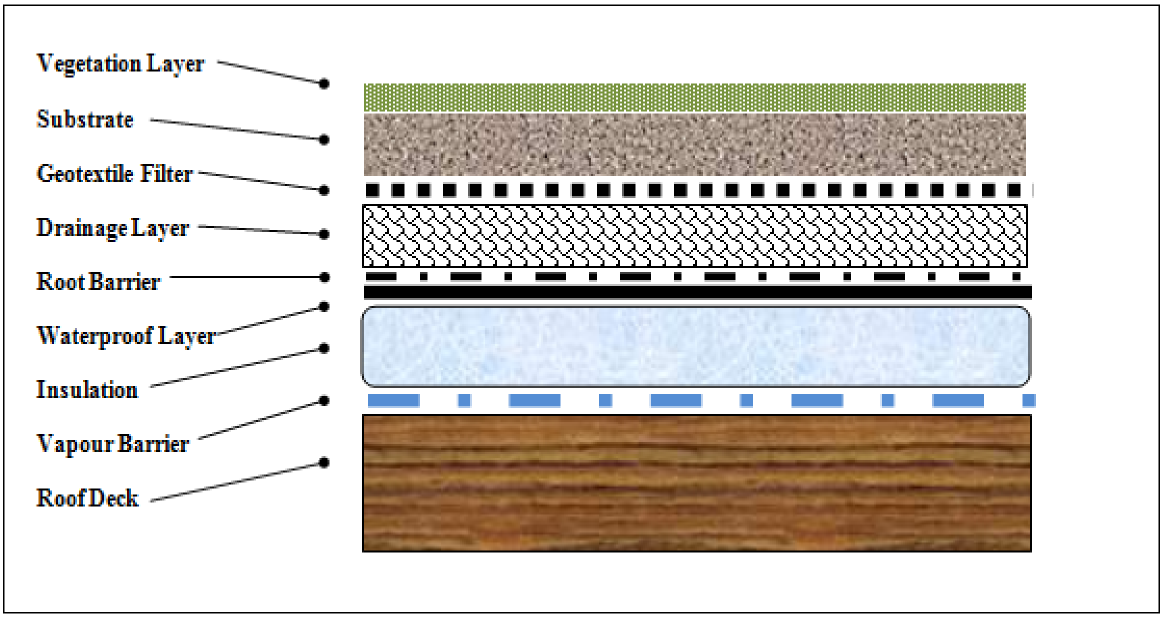


Figure 10: *Warm Green Roof Construction*

3.2 Inverted Warm Green Roof Construction

Insulation is located on the exterior of the waterproof layer. The insulation must be impervious to water eg. extruded polystyrene). The waterproof layer acts as a vapour barrier, preventing condensation between itself and the deck. The thermal insulation layer (as well as the vegetation layer and substrate) protects the waterproof layer from temperature extremes. The root barrier must be located below the insulation.

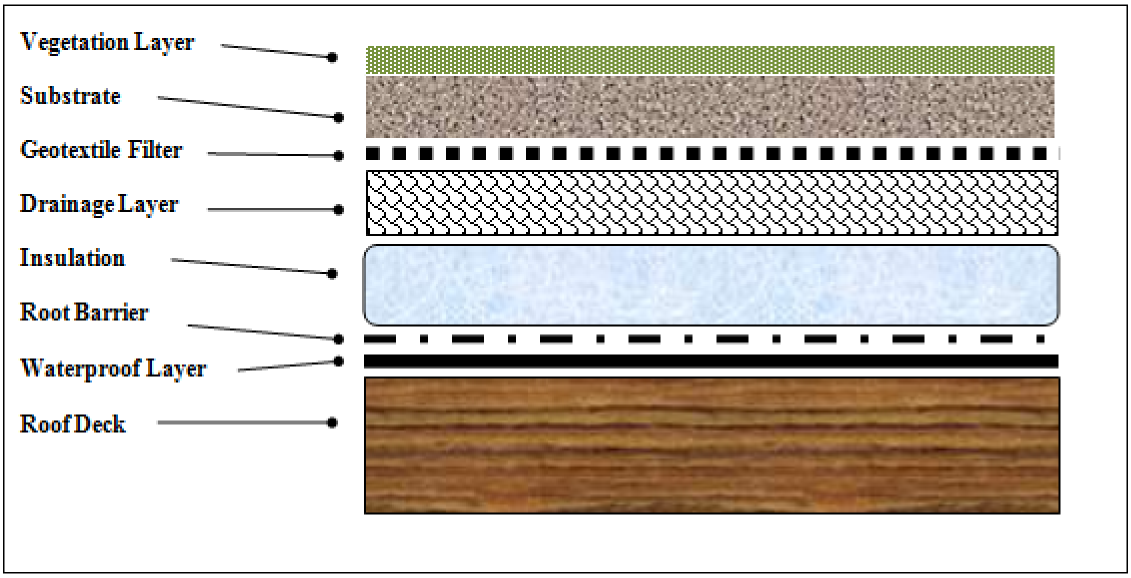


Figure 11: *Inverted Warm Green Roof Construction*

3.3 Cold Green Roof Construction

Insulation is located on the interior side of the roof. The deck is not warmed by the building interior and ventilation is required above the insulating layer to reduce condensation. The waterproof layer is protected from UV radiation and extremes of temperature by the vegetation and substrate layers.

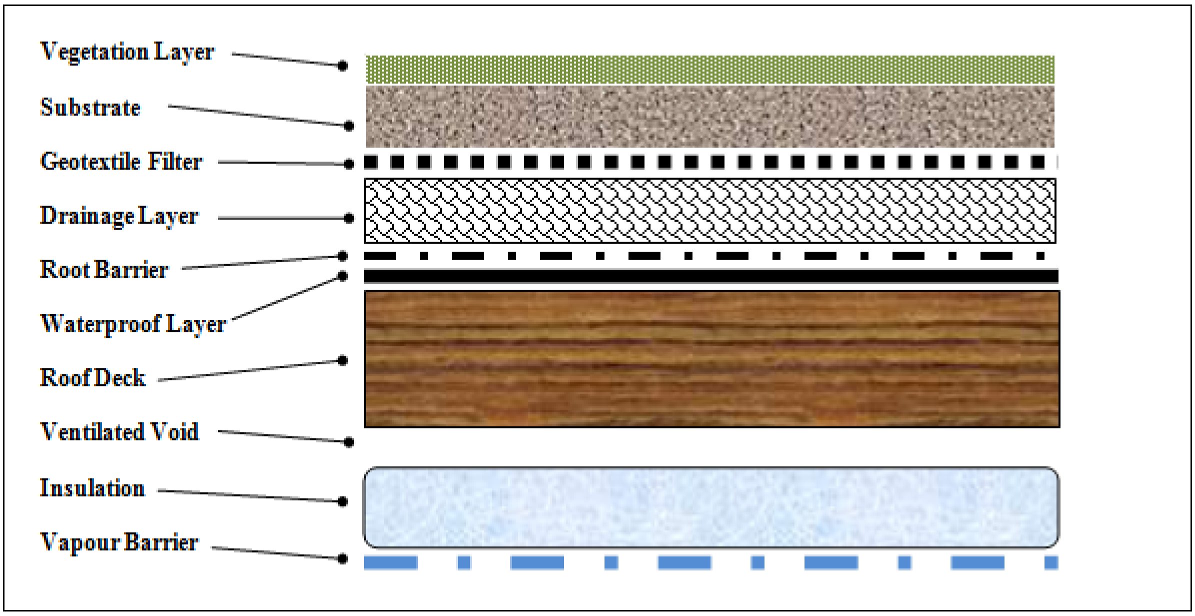


Figure 12: *Cold Green Roof Construction*

3.4 Structural Support of Green Roofs

When a green roof is designed for a new or existing building, the weight of the roof must be accounted for. The saturated weight of the soil must be measured when calculating the implied loads.

The amount of structure required to support a green roof depends primarily on the type of green roof system installed: intensive or extensive. The nature of intensive roofs may require the inclusion of a reinforced concrete or steel structure for additional support [8], due to the increased substrate depth of up to 1500mm. This means the cost of construction will rise substantially. Therefore, intensive green roofs are generally applied to large structures with multiple levels as the required structural support is already in place.

For low-rise buildings extensive roofs are most commonly used as the cost of additional structural support required for intensive green roofs makes the construction very expensive.

Although less versatile than intensive green roofs, they are cheaper in terms of construction and maintenance due to the reduced substrate depth (typically less than 200 mm) [3].

3.5 Green Roof Components

The four main components of a green roof system (the root barrier, drainage layer, substrate and vegetation layer) are discussed in more detail as follows.

3.51 Root Barrier

The root barrier is an essential part of a green roof system because it prevents the roots of vigorous plant species penetrating through to the waterproof membrane. The type of root barrier used will depend upon the system and the type of plants used and is therefore usually specified by the green roof supplier or waterproofing supplier.

3.52 Drainage Layer

The purpose of the drainage layer is, in combination with the substrate, to control the water retention properties of the green roof [3]. The key benefits of the drainage layer include:

- Reduction of water ponding on the roof. This is particularly important on flat roof constructions as prolonged water ponding can result in structural fatigue.
- Providing the correct drainage conditions to allow desired vegetation to survive and flourish. If a green roof is too free draining then plants may die back during dry periods. Conversely, if the drainage is insufficient then waterlogging may occur which can cause plants to rot.
- The control of the amount and timing of rainwater runoff. This contributes to the management of stormwater runoff and helps to meet planning and regulatory constraints.

Drainage layers can be divided into two main categories:

1. Granular materials including sand and gravel, lava and pumice, expanded clay and slate. Recycled materials such as foamed glass, crushed brick and roof tiles.

2. Modular systems which typically comprise of profiled or dimpled sheets of plastic. These act as reservoirs to hold water, with cross drainage for excess water.

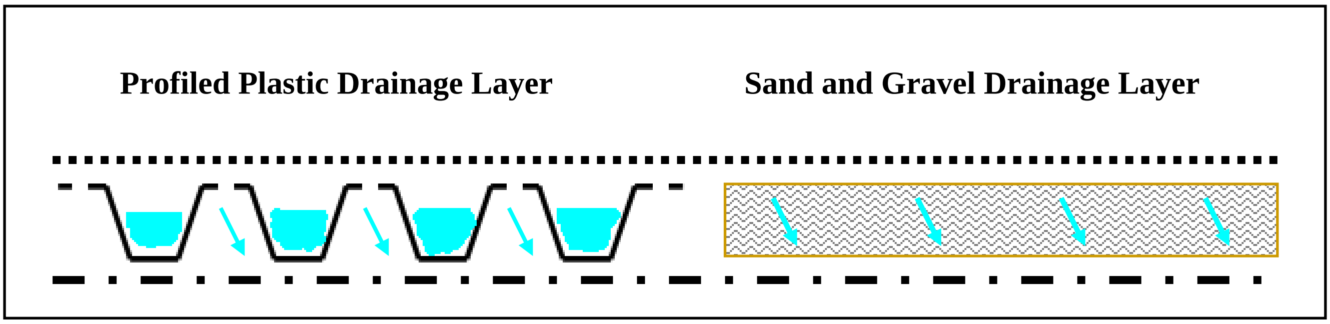


Figure 13: *Typical Example of Green Roof Drainage Systems*

3.53 Substrate

The purpose of the substrate layer is to provide the mechanical strength, open pore structure, nutrients, chemical composition and drainage properties that the desired plant species require [3].

Intensive green roofs require a deep and fertile substrate layer. The topsoil is relatively dense and heavy when saturated, therefore load and maintenance requirements are generally an accepted part of intensive roof design.

In contrast, extensive roof systems are generally implemented where weight and maintenance requirements are key design constraints. Therefore substrates are lightweight with a low nutrient content.

3.54 Vegetation Layer

There are four main methods of establishing vegetation on a green roof:

1. **Vegetation Mats** are the most expensive way of greening a roof but provide 90-100 % vegetation cover when installed.

2. **Plug Planting** involves planting a pot grown plant directly into the substrate. This allows for the easy mixing of plant species but takes longer to establish vegetation coverage.

3. **Seeds and Cuttings** can be hand distributed or sprayed onto a roof in a gel or hydromulch that holds the seeds in place until plants are established. Cost effective but is a slow method of achieving vegetation cover.

4. **Natural Colonisation** is the cheapest and most environmentally and ecologically beneficial way of vegetating a green roof. It involves allowing a bare substrate to colonise naturally in sympathy with its local environment. However, this can result in varying aesthetic appeal.

The choice in vegetation primarily depends upon the type of green roof - intensive or extensive – and the structural loads these impose. Other factors include: aesthetic appeal, cost, runoff characteristics and biodiversity benefits.

4 Benefits of Green Roofs

Green roofs have several social, economic and environmental benefits and can contribute positively towards issues such as biodiversity, climate change mitigation, flood prevention and increasing green space in urban areas. The main benefits of green roofs from Brownlie

(1990) [9], Johnston (1995) [10], Johnston & Newton (1993) [11], Osmundson (1999) [12] and Wells (2001) [13] can be summarised as follows:

Environment

- attenuation of storm water run-off
- run-off attenuation reduces sewer overflows
- option of cleaning and recycling grey water (wastewater generated from domestic activities such as laundry, dishwashing, and bathing which can be recycled on-site for uses such as landscape irrigation and constructed wetlands)
- absorption of air pollutants and dust
- reduction in the 'urban heat island' effect
- increased humidity
- absorption of noise
- absorption of electromagnetic radiation
- helping to absorb greenhouse gases (particularly CO_2) and giving off oxygen
- use of recycled materials

Ecology and Biodiversity

- provision of new wildlife habitat
- replacement of habitat lost through development
- provision of quiet refuges
- providing links or stepping stones in green space networks
- often only available green space in urban core

Amenity

- more options for designers
- hides grey and uniform roofing materials
- screens equipment
- provides attractive views of vegetation

- extension of park system
- provides gardens – more recreational space

Health

- psychological benefits of contact with nature
- improved air quality – helping to reduce respiratory diseases
- improved water quality

Building Fabric

- protecting the roof from UV radiation
- protecting the roof from mechanical damage
- reducing diurnal/seasonal temperature changes in roof
- may improve thermal insulation

Economic

- extension of roof life
- attracts buyers/tenants
- may reduce water/sewer charges
- reduce heating and air conditioning costs
- use of recycled materials from site reduces costs

Some of the key benefits of green roofs are discussed in more detail as follows.

4.1 Biodiversity

Green roofs have considerable potential to provide biodiversity benefits; especially in urban areas. They can help in meeting national, regional and local biodiversity action plan targets which were implemented in 1994 (after the UK signed up to the convention on biological diversity at the UNCED conference in Rio, 1992) [3]. Some of the main advantages green roofs provide for improving biodiversity include:

- Helping to remedy areas of deficiency, ie providing new habitat in areas which are currently lacking in wildlife habitat
- Creating new links in an intermittent network of habitats, thereby facilitating movement and dispersal of wildlife
- Providing additional habitat for rare, protected or otherwise important species [8]

4.2 Sustainable Drainage

Surface water drainage systems that follow the principles of sustainable development are collectively referred to in the UK as sustainable drainage systems (SUDS). In urban areas, up to 75% of rainwater becomes run-off due to the development of ground space through which rain water cannot be lost by permeation [14]. Therefore, it is important to try and replicate natural drainage systems and processes in order to reduce this run-off. SUDS objectives are to:

- Replicate natural drainage as closely as possible
- Control the quantity and quality of the run-off from development sites
- Maximise amenity and biodiversity opportunities

Once established, a green roof can significantly reduce both peak flow rates and total runoff volume of rainwater from the roof compared to a conventional roof. Green roofs store rainwater in the plants and substrate and release water back into the atmosphere through evapotranspiration [15]. The amount of water that is stored on a green roof and then evapotranspired into the atmosphere is dependent on the depth and type of growing medium, type of drainage layer, vegetation used and regional weather. Green roofs can easily meet SUDS standards of preventing run-off from rainfall events of up to 5mm.

In summer, green roofs can retain 70–80% of rainfall and in winter they retain 10–35% depending on type and depth of substrate and type of vegetation [16]. During winter, there is greater rainfall and less evapotranspiration by the plants because there is less growth.

Overall, the deeper the substrate the greater the average annual water retention. Intensive green roofs with deeper substrates can hold up to 20% of the rainfall absorbed for up to 2 months [12].

4.3 Climate Change Mitigation and Adaption

In the UK, buildings are responsible for 45 percent of CO_2 emissions: 27% of the UK's emissions come from homes, 18% from non-residential buildings [17]. A high proportion of these emissions are from heating and cooling the internal environment. Reducing the energy consumption of the UK's buildings will reduce their contribution to climate change. The IPCC (Intergovernmental Panel on Climate Change) have said that buildings provide some of the greatest, most cost effective and fastest opportunities to tackle climate change. Green roofs can significantly reduce the cooling loads of buildings, resulting in reduced air cooling requirements and therefore reduced energy consumption and the associated output of atmospheric carbon dioxide.

The insulation levels required to meet current UK Building Regulations ensure that the internal thermal performance is largely isolated from external environmental conditions (roofs should meet a maximum U-value of 0.16 W/m^2K). Therefore, the effect of green roofs on thermal insulation on new builds is negligible. When retrofitting a green roof, green roof materials should not be used as a substitute for insulation.

Green roofs can also reduce the daily temperature fluctuations of building roofs. The diurnal temperature range (the difference between minimum and maximum temperatures over a 24 hour period) at the waterproof layer of a green roof is significantly less than that of a conventional bitumen covered roof; and is typically below 10^oC during the summer for an extensive green roof. Some of the factors which affect the thermal properties of a green roof include:

- Evapotranspiration from the plants and substrates, which uses a considerable proportion of the incoming solar radiation compared with non-green roofs
- Green roofs have a large thermal mass, which stores energy and delays the transfer of heat to and from the building fabric
- The absorption of solar radiation by plants for photosynthesis
- Plants have a higher equivalent albedo (solar radiation reflectivity) than many standard roof surfaces

The reduction in the diurnal temperature range of green roofs also extends the life of the water proof layer. The green roof also protects the waterproof layer from UV light (which disrupt the chemical bonds) and from puncture by falling objects [3].

Overall, a smaller proportion of incoming solar radiation is converted into heat on a green roof - in comparison with a conventional roof – so less heat is transferred to the wider environment. This is an important factor affecting the local urban climate.

4.4 Reducing the Urban Heat Island Effect

The urban heat island effect describes the phenomena of higher average temperatures in urban areas compared with surrounding rural areas. This can lead to an increase in air-born pollution and an increased use of air conditioning.

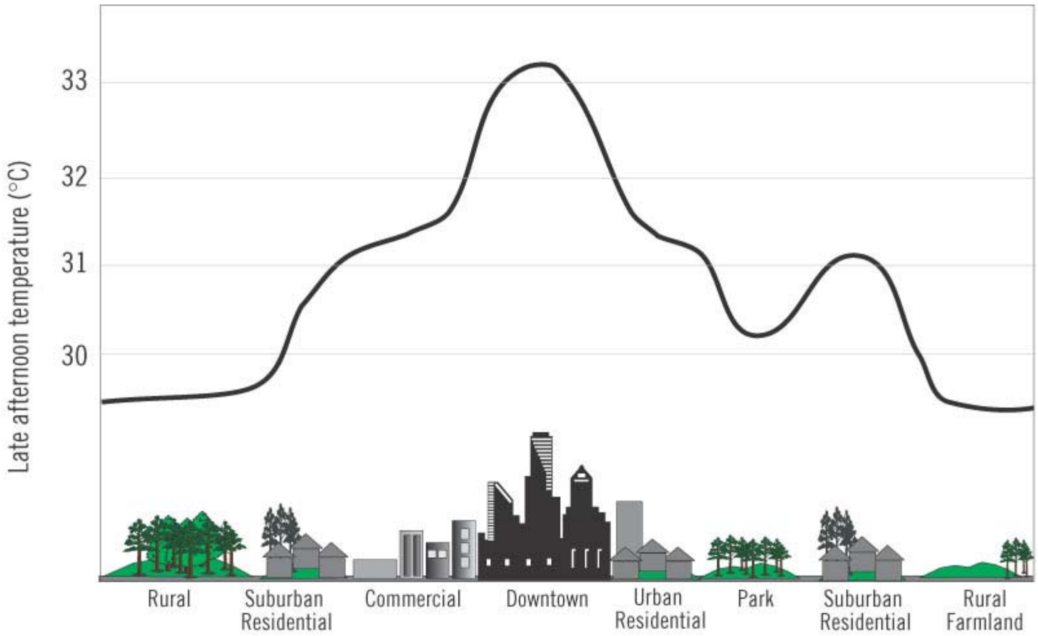


Figure 14: *Example of Urban Heat Island Effect* [18]

A number of complex factors contribute to the urban heat island effect. These include [19]:

- Reduction of evaporating surfaces – more energy turned into sensible heat and less into latent heat
- Thermal properties of materials – increased storage of sensible heat in building fabric
- Anthropogenic heat released – from combustion of fuels and metabolism of animals/people
- Canyon radiative effect – decrease of long-wave radiation lost to the sky and retained in the urban area due to radiation interchange between especially tall buildings within relatively narrow streets and reduction of albedo due to multiple reflection of short-wave radiation between building surfaces

- Urban greenhouse effect – increase of long-wave radiation reflected from the polluted, warmer urban atmosphere
- Reduced turbulent heat transfer – transfer of heat to the air is reduced due to less air turbulence in streets

One solution for reducing the effect of the urban heat island effect is to introduce more vegetation into the urban environment to provide shading and cooling through evapotranspiration. Another solution is to increase the reflectiveness (or albedo) of roofs and other exposed surfaces. This will reflect a higher proportion of the received solar radiation back to the sky; producing less sensible heat.

Green roofs combine both of these solutions and are increasingly being proposed as mitigation for the urban heat island effect. Green roofs have a high equivalent albedo of between 0.7 and 0.85, depending upon the availability of water for evapotranspiration [20]. Evaporative cooling on green roofs works by increasing humidity and reducing the amount of energy available for conversion into sensible heat. During warmer, drier months the reduced moisture content of a green roof reduces the real evapotranspiration rate compared with the theoretical potential evapotranspiration rate, thus reducing the cooling effect. Therefore, in warmer, drier months irrigation may be required to maintain the evapotranspiration benefits of green roofs.

4.5 Sound Insulation

The combination of soil, plants and trapped layers of air within green roof systems can act as a sound insulation barrier. Sound waves are absorbed, reflected or deflected. The substrate tends to block lower sound frequencies and the vegetation blocks higher frequencies. The amount of sound insulation a green roof provides mainly depends on the depth of substrate used.

Research has shown that a depth of growing medium of 20-100 mm can achieve an extra sound pressure level attenuation of 10-40 dB, depending on frequency [15]. This compares with a typical reduction of 43 dB for a 100 mm concrete wall. Compared with a conventional roof, green roofs can reduce sound within a building by 8 dB or more [21].

4.6 Building Fabric

When vegetation is introduced to roofs, the underlying materials of the structure are effectively given a blanket of protection. This blanket prolongs the roofs lifespan and reduces the stress applied to the roofing materials [6].

The key benefits for protecting the building fabric for green roofs are [8]:

- Protecting the roof from ultra violet radiation.
- Reducing diurnal/seasonal temperatures changes in the roof.

Ultra violet light can have a damaging effect on roofing materials when high levels of exposure occur. The ultra-violet radiation causes roofing materials to lose their inherent strength which can result in substantial maintenance costs. Likewise, large fluctuations in annual and diurnal temperatures cause roofing materials to expand and contract [8]. The stress incurred by these fluctuations can be sufficient to cause the eventual failure of the roof.

The layer of vegetation acts as a buffering system to the physical impact imposed by ultra-violet radiation and temperature variations within the roof. The inclusion of a barrier system, against root penetration, is essential when providing protection to the waterproof membrane.

4.7 Green Roofs and Solar Panels

The perception that buildings can either have green roofs or solar production at roof level, but not both, is a mistaken one. There is substantial evidence from Germany that the use of solar thermal and photovoltaics (PV) with green roofs provides dual benefits in terms of energy production and energy saved.

Figure 15: *Green Roof with Photovoltaic Panels* [5]

PV A-Frame panels at roof level are known to work more efficiently when installed on a green roof rather than a on a conventional surface. The green roof element can increase the efficiency of PV panels by reducing temperature fluctuations at roof level and by maintaining a more efficient microclimate around the PV Panels. Crystalline silicon PV panels lose roughly 0.5 % per °C in efficiency above 25°C. The green roof serves as a natural cooling mechanism, thereby maintaining the panels' efficiency [22].

Solar Panels can only be installed on green roofs with extensive vegetation and must be installed above vegetation level to avoid shading of the panels. The panels are installed on special frames of aluminium which are attached to plastic boards located beneath the substrate [5]. This allows vegetation to grow beneath the panels. As the solar panels are mounted on plastic boards this distributes the load evenly across the roof; avoiding point loads.

5 UK Policy on Green Roofs

There are currently no direct references to green roofs in the UK Building Regulations, only to the general standards of roof construction. However, green roofs can be constructed to meet these standards.

Part L of the Building Regulations aims to substantially increase the energy efficiency of new and existing buildings and green roofs can contribute towards this by increasing insulation (as a retrofit on existing buildings).

Local authorities still require the correct guidance on green roofs to ensure that the highest standards are being met: both by suppliers and installers. This lack of a formal standard has led to fears that sub-standard systems are being allowed to be installed and that these will damage the reputation of green roofs.

In the absence of any British standards, most manufacturers and installers rely upon the German Landscape Development Research Society (FLL) guidelines for the design and construction of green roofs [23].

6 Green Roof Research

Previous research concerning green roofs has primarily focused on two key areas: thermal performance and rainwater runoff performance. The quantitative analysis of these two areas has gained increasing importance in recent years as green roofs become more established.

6.1 Thermal Performance of Green Roofs

A number of studies on the thermal performance of green roofs have been carried out as this is one of the most attractive benefits [24]. Green roofs can dissipate the heat absorbed from the sun in several effective methods, thereby reducing the heat transferred into the building.

Wong et al. [25], Theodosio [26], Barrio [27], Takakura et al. [28], Onmura et al. [29] and Sailor [1] have all studied the energy balance of green roofs and concluded that the dominant way for green roofs to dissipate the heat absorbed is through evapotranspiration. However, some earlier studies have suggested that thermal radiation from leaves was the dominant form of heat dissipation [30, 31].

6.11 Reduction of Heat Flux and Solar Reflectivity

Typical dark roof materials can reach temperatures as high as 80 ^{o}C during summer months – nearly 3 times as high as an equivalent green roof [32]. As mentioned, green roofs dissipate heat absorbed through evapotranspiration and also through improved reflectivity of incident solar radiation. The ratio of total reflected to incident electromagnetic radiation is defined as albedo. The albedo of green roofs is equivalent to that of a bright white roof; with an an equivalent albedo of 0.7 - 0.85 compared with 0.1 - 0.2 for a bitumen/tar/gravel roof [33].

A study by Wong et al. [25] found that, during summer, heat absorbed by conventional dark roofs during the day continued to enter the building during the night. This effect was greatly reduced for a green roof thus reducing the cooling load for rooms below. A similar study by Lui and Minor [34] found that heat gain through an extensive green roof was reduced by an average of between 70 – 90 % during the summer and heat loss by 10 – 30 % in winter (compared with an insulated steel deck roof).

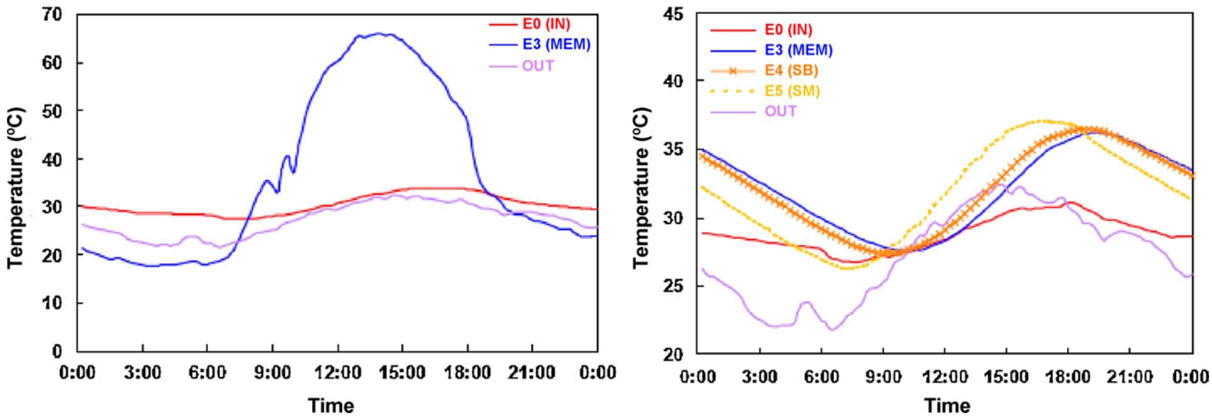


Figure 16: *Summer Temperatures of Reference Roof and Green Roof* [34]

Figure 16 shows the comparison between the insulated steel deck roof and the green roof with thermocouples located under the roof (E0), waterproof membrane (E3), subsrate (E4), in the middle of the substrate (E5) and outside measuring the ambient air temperature (OUT). As can be seen, the peak temperature is reduced by around half and the internal temperature peak is slightly delayed (although the thermal insulation of the reference roof reduced the transfer of any heat flux).

6.12 Thermal Mass

As well as reducing diurnal temperature fluctuations, the thermal mass of a green roof can also improve the insulation properties of a building. The UK building regulations require that the roof U-value be 0.25 W/m^2 or less for all types of buildings [35]. Prior to 1965, there were no insulation requirements in building standards and since then the U-value has gradually decreased from 1.42 W/m^2. This means there is a lot of old building stock which will benefit from the insulating properties of green roofs.

Although green roofs are predominantly seen as a passive cooling technique (in terms of thermal properties), there is evidence from a study by Nichaou et al. [36] suggesting that winter heating savings are larger than summer cooling savings – a result especially beneficial for the UK.

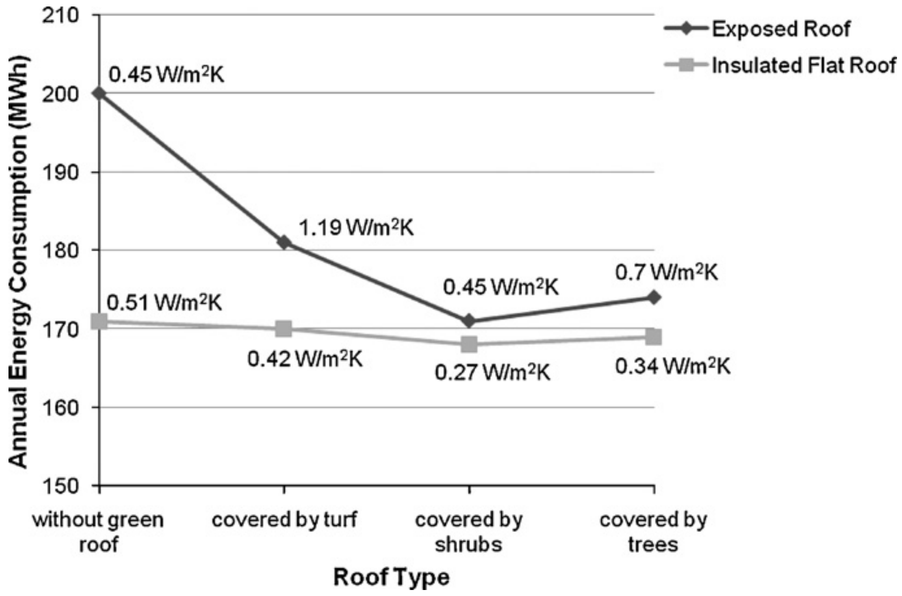


Figure 17: *Annual Energy Consumption of Different Roof Types* [25]

Figure 17 shows the results of a study by Wong et al. [25] on the insulating properties of different types of green roof system: from extensive to intensive. The study highlights how for uninsulated roofs, the retrofitting of extensive green roofs can significantly reduce annual energy consumption (around 20 MWh for this study).

6.13 Substrate Thickness and Moisture Content

Lui and Minor [34] measured the heat transfer difference between a 100mm, lighter coloured growing medium compared to a 75 mm deep green roof, compared also to a reference roof with the same structure (insulated steel deck). The increased substrate depth displayed a lower heat gain and loss across the measured roofing system. They identified little contribution from the vegetation, indicating that the thermal performance was improved by the thicker substrate. Barrio [27] used a mathematical model to assess the summer cooling potential of green roofs in Athens, Greece. She found that the thickness of the soil layer, its relative density, along with moisture content, influenced the thermal diffusivity of the soil. As the density decreased from 1500 kg/m^3 to 1100 kg/m^3, the thermal conductivity of the soil decreased; hence the heat flux through the roof decreased. Additional air pockets in the less dense soil led to an increase in its insulating properties. Conversely, as soil moisture content decreased from 40 % to 20 %, the heat flux through the roof increased, suggesting that a wetter green roof is a better insulator.

However, the previous study mentioned by Wong et al. [25] suggests that wetter substrate is a poor insulator compared to dry. With every 100 mm increase in substrate depth, the thermal resistance of the dry clay soil increased by 0.4 m^2K/W compared to only 0.063 m^2K/W for clay soil with 40 % moisture content.

6.14 Evaporative Effect and Substrate Moisture Content

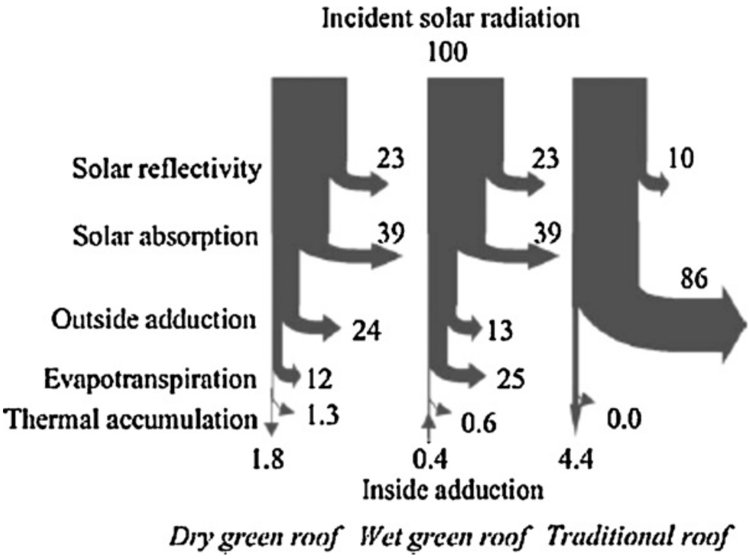


Figure 18: *Energy Exchanges of Dry/Wet Green Roofs and a Traditional Roof (Summer)* [37]

Figure 17 shows the energy exchanges on dry/wet green roofs and a traditional roof. The study by Lazzarin et al. [37] showed that the dry green roof reduces the incoming heat flux by 60 % (in comparison with the traditional roof). The additional evapotranspiration of the wet green roof provides an additional passive cooling effect – removing heat from the building.

A previous study by Feng et al. [38] showed that 58 % of the heat loss from a green roof was by evapotranspiration and 30.9 % by long wave radiative exchange – with 1.2 % stored or transferred to the room beneath.

6.2 Rainwater Runoff Performance of Green Roofs

The rainwater runoff performance of green roofs (also known as the hydrologic performance) can play an important role in the development of sustainable drainage – especially in areas where space is at a premium.

As mentioned previously, a green roof changes runoff compared with that from a conventional roof through lowering (attenuation) and delaying the peak runoff (there is a time lag between the peak from a hard roof and a green roof for the same rain event).

6.21 Rainfall Runoff Relationship with Storage Capacity

The effect of green roofs on stormwater runoff reduction is dependent upon the depth of substrate, its moisture content and the size of rainfall event. Other factors include the age of the roof, type of vegetation cover and the slope of the roof [39].

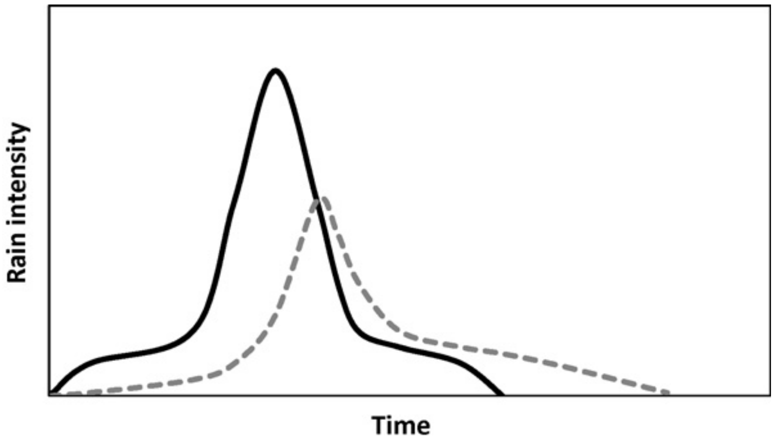


Figure 19: *Runoff from Green Roof (dashed line) for given Rain Event (solid line)* [39]

The relationship between a green roofs water retention and the size of rainfall event (and its intensity) has been investigated in a number of studies. Carter and Rasmussen [40] found an inverse relationship between the amount of rainfall and the percentage of rain retained. For small rainfall events (< 25.4 mm) 88% was retained, medium (25.4 – 76.2 mm) more than 54% was retained and for large (> 76.2 mm) 48% was retained. The conditions regarding the humidity of the roof materials before the storms were not given.

Similarly, Simmons et al. [41] found that small rain events of < 10 mm were all retained in the green roofs. For rain event of 12 mm the retention between the green roofs varied from 88 % to 26 % depending on the substrate and drainage type. The rain events of 28 mm and 49 mm showed a retention of 8 - 43 % and 13 – 44 % respectively. It was further observed that the retention depends upon the rain event intensity changes as well as the rain event size.

6.22 Role of Vegetation

Most studies show that the type and depth of substrate has the major influence on green roof water capacity and not the vegetation type.

However, the type and cover of vegetation does play a role in the water retention and runoff characteristics of a green roof. This is mainly during summer months, when there is lower water availability and higher temperatures.

6.23 Influence of Slope

The influence of slope on the runoff and retenetion characteristics of green roofs varies between studies. Some studies such as Bengtsson [42] find no correlation between roof slope and runoff, whereas a study by Getter et al. [43] found that runoff retention may depend upon the slope.

The effect of the roof slope combines with other factors such as the substrate properties, intensity of rainfall event, flow conditions, the design and type of green roof layers (especially drainage).

The study mentioned by Getter et al. [43] found that for different rainfall events (light < 2 mm, medium 2 – 10 mm, heavy > 10 mm) both the type of rainfall event and slope had significant influence over water retention. Water retention for the lowest gradient of slope was 85 %, whereas for higher gradients 75 % of precipitation was retained (as an average of results). It was also found that retention was higher for light rain events (94 %) than for heavy rain events (63 %) - as would be expected.

7 Methodology

A methodology was established to assess the thermal performance of a green roof test rig with an extensive green roof system installed. A methodology was also established to compare the rainfall runoff performance of an extensive green roof system with a Photovoltaic (PV) panel. For this experiment a 5 mm thick perspex sheet was used to replicate a PV panel.

7.1 Green Roof Test Rig for Thermal Performance

A test rig was set up to measure the thermal performance of a green roof. A roof angle of 10 degrees was chosen for a shallow flat pitch roof. The area of the roof was 1.2 m^2. Four thermocouples were attached at various points on the green roof test rig to measure under roof, substrate, plant and ambient air temperature. A humidity sensor was placed in the substrate in order to measure its moisture content. A data acquisition system was setup using National Instrument hardware 9211 and 6008. NI DAQmx and Labview Signal Express were used to log, analyse and present the data on a laptop.

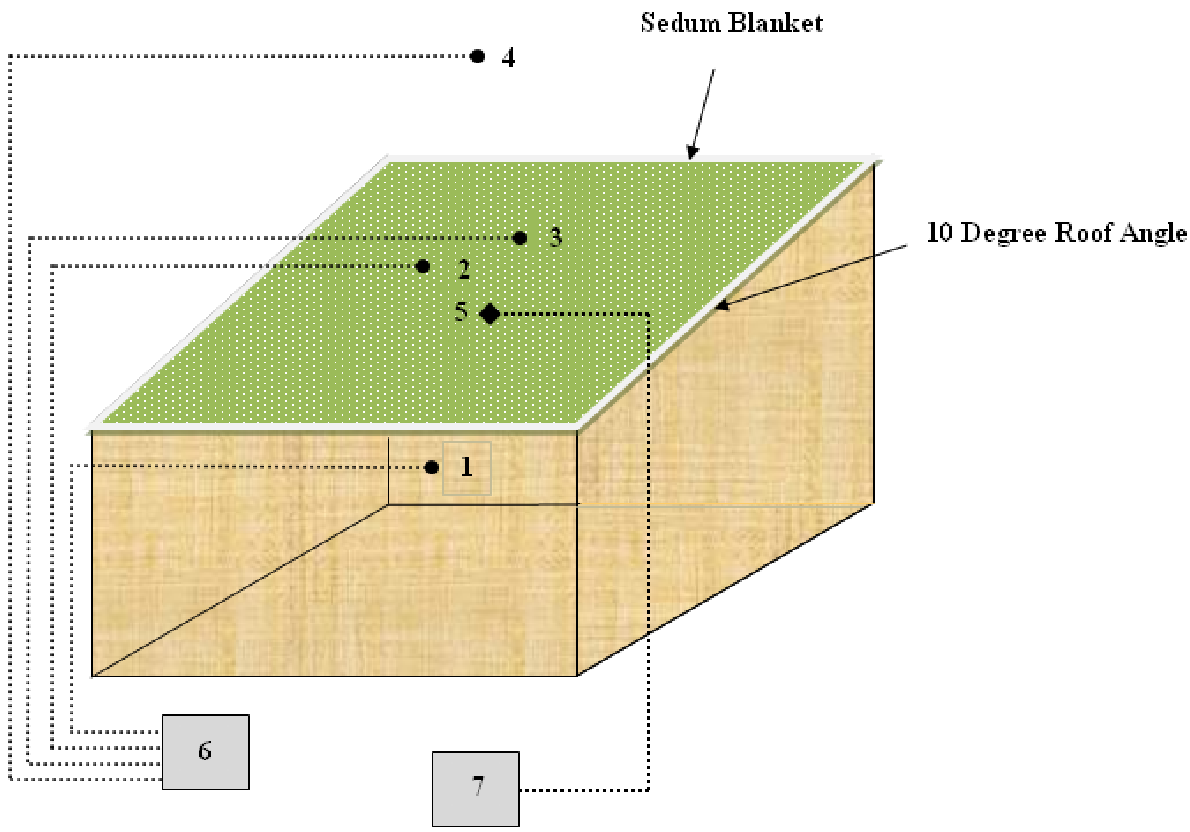


***Figure 20**: Green Roof Test Rig for Thermal Performance*

1. Under Roof Thermocouple
2. Substrate Thermocouple
3. Plant Thermocouple
4. Ambient Air Thermocouple
5. Humidity Sensor
6. NI USB-9211 Measuring Device
7. NI USB-6008 Measuring Device

Figure 21*: Green Roof Test Rig*

7.11 Sedum Blanket

The sedum blanket used for the green roof test rig was provided by Bauder Limited.

The Bauder Xero Flor extensive green roof system is constructed using low maintenance sedum planting (succulents). The plants are grown on a 'blanket' that is harvested like turf and provide full coverage and increased protection for the waterproof layer.

Figure 22*: Bauder XF301 Sedum Blanket* [44]

For the specified shallow flat pitch roof 10 degrees, Bauder recommended the Bauder XF301 Sedum Blanket. The vegetation blanket is pre-cultivated on a patented nylon loop and geo-textile base carrier with substrate. This is attached to an integral 8 mm moisture retention fleece which retains moisture after rainfall allowing plants to take up the water for future storage.

The mineral content of the substrate consists of recycled crushed brick and expanded clay shale and the organic component is composted pine bark. It has a pH value of 6.5 – 7 and the moisture retention fleece is made from 80 % man-made and 20% organic recycled fibres. The thickness – excluding vegetation – is 28 mm and the saturated weight is 44 kg/m^2.

Once installed, the sedum blanket requires little maintenance with biannual checks for dead vegetation and blockage of drainage outlets.

For more information on the Bauder XF301 Sedum Blanket see ***Appendix 1***.

For this project, a NDC waterproof membrane was used instead of the recommended Bauder Thermofol PVC system for ease of installation.

7.12 NI USB-9211

The NI USB-9211 measuring device is designed specifically for thermocouple measurements and acquires and logs up to four channels of thermocouple data.

***Figure 23**: NI USB-9211 Measuring Device*

It was used to acquire the under roof, substrate, plant and ambient air temperature.

For further technical information on the NI USB-9211 see the NI website.

7.13 <u>Thermocouples</u>

Type K (chromel – alumel) thermocouples were used to measure the roof, substrate, plant and ambient air temperature. The thermocouples were attached to the NI USB-9211 as shown below.

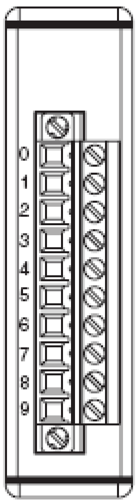
Module	Terminal	Signal	Thermocouple
	0	TC0+	**Under Roof**
	1	TC0–	
	2	TC1+	**Substrate**
	3	TC1–	
	4	TC2+	**Plant**
	5	TC2–	
	6	TC3+	**Ambient Air**
	7	TC3–	
	8	No connection	
	9	Common (COM)	

***Figure 24**: NI USB-9211 Thermocouple Terminal Assignments*

The thermocouples were spot welded at the Mechanical Engineering laboratories at the University of Strathclyde.

Figure 25 shows how the type K thermocouples were attached to the NI 9211 device.

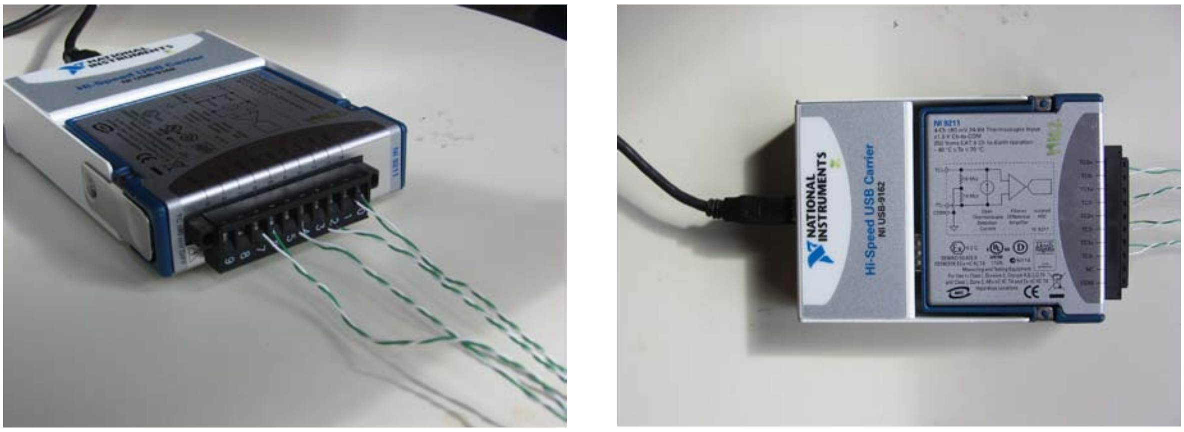


***Figure 25**: NI USB-9211 Thermocouple Attachment*

Figure 26 shows how the thermocouples were placed on the green roof test rig.

***Figure 26**: Under Roof and Substrate Thermocouple Placement*

As can be seen in Figure 27, for the type K thermocouple the green wire is positive and the white wire is negative.

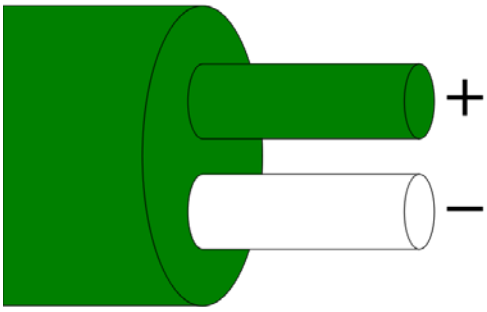


***Figure 27**: Type K Thermocouple*

Figure 28 shows the thermocouples attached to the green roof test rig.

***Figure 28**: Green Roof Thermocouple Placement*

7.14 <u>NI USB-6008</u>

The NI USB-6008 Measuring Device provides basic data acquisition for applications such as simple data logging, portable measurements and academic lab experiments.

***Figure 29**: NI USB-6008 Measuring Device*

It was used to acquire the relative humidity (moisture content) of the substrate.

For further technical information on the NI USB-6008 see the NI website.

7.15 Humidity Sensor

A Honeywell HIH-4000 series humidity sensor was used to measure the moisture content of the substrate on the green roof.

Figure 30*: HIH-4000 Humidity Sensor*

The humidity sensor was connected to the NI USB-6008 using a three wire connection via a terminal block.

The dimensions and terminals of the humidity sensor are shown in Figure 31.

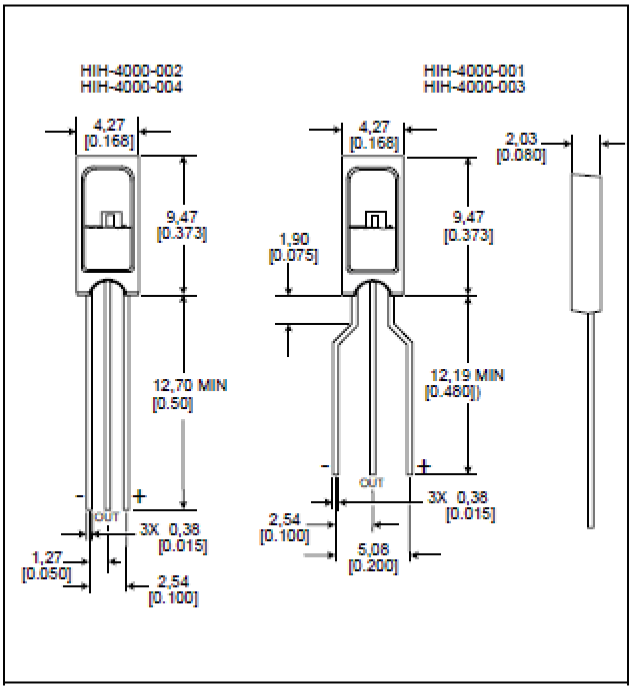


Figure 31*: HIH-4000 Dimensions and Terminals*

Figure 32 shows the humidity sensor located in the substrate in order to measure the moisture content.

***Figure 32**: Humidity Sensor Located in Substrate*

The grey, brown and black wires are the signal, 0 V and +5 V wires respectively. Figure 33 shows the terminal assignments of the signal, 0 V and +5 V wires.

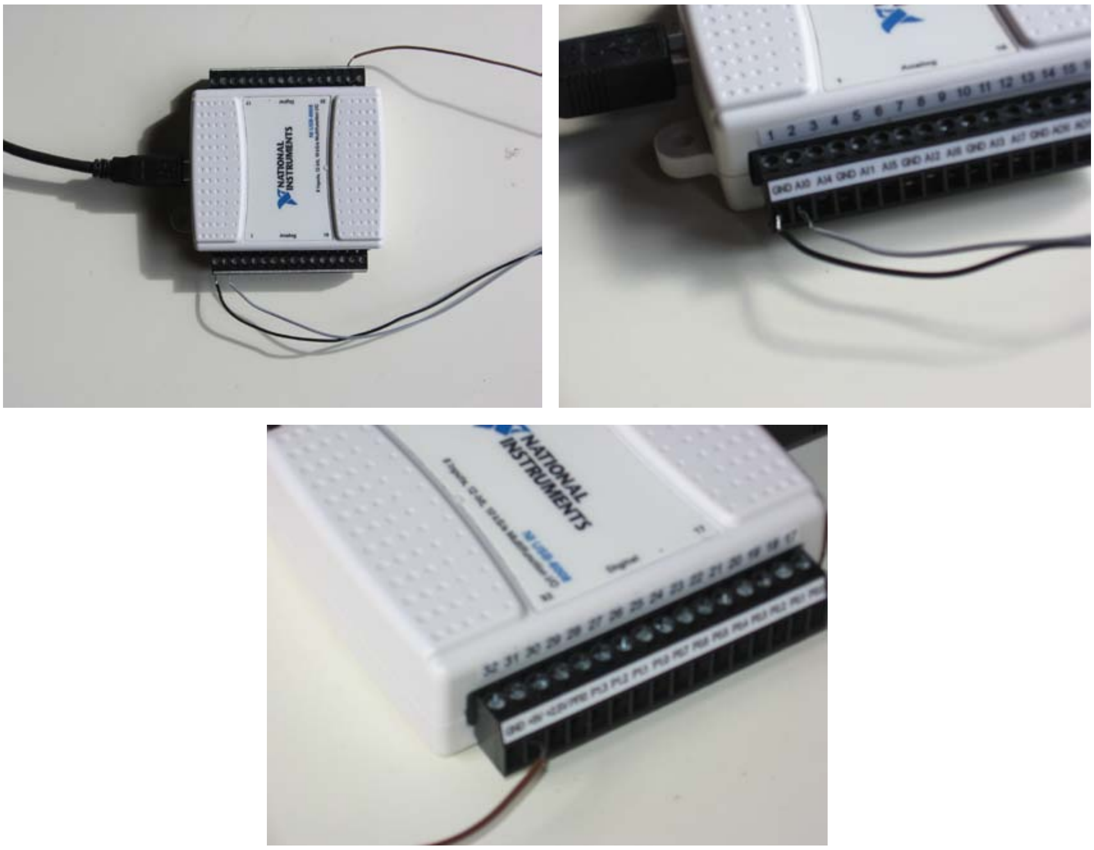


Figure 33: *NI USB-6008 Terminal Assignments*

Terminal	**Wire**
GND	Black
AI 0	Grey
+5 V	Brown

Table 2: *NI USB-6008 Terminal Assignments*

The relationship between the output voltage of the humidity sensor and the relative humidity (moisture content) is shown in Figure 34.

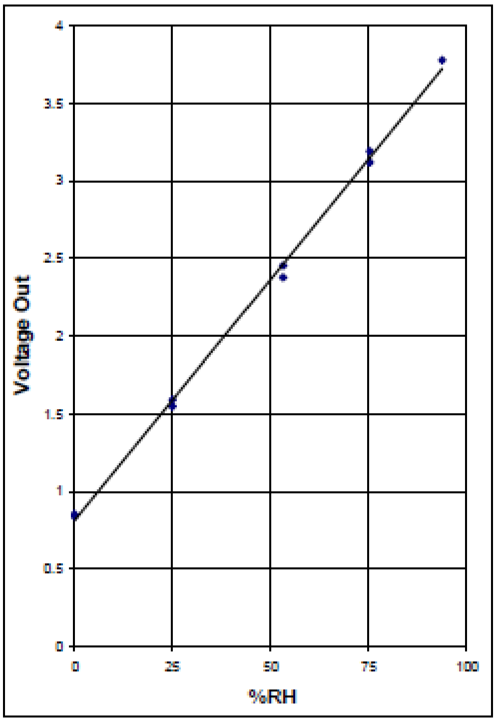


Figure 34: *Voltage Output vs. %RH*

For further technical information on the HIH-4000 humidity sensor refer to uk.rs-online.com.

7.16 NI DAQmx and Labview Signal Express

NI DAQmx and Labview Signal Express software were installed prior to the connection of NI devices 9211 and 6008.

Once the NI devices were connected to the laptop via USB, the data acquisition system was ready for testing and running/recording results.

7.161 Data Acquisition Method

The following procedure was followed in Labview Signal Express:

- Add Step
- Acquire Signals
- DAQmx Acquire
- Analog Input

For the first step, temperature was selected for thermocouple measurements and for the second step; voltage was selected for relative humidity measurements.

7.162 Thermocouple Step

Figure 35 shows the thermocouple setup for the NI USB-9211 device.

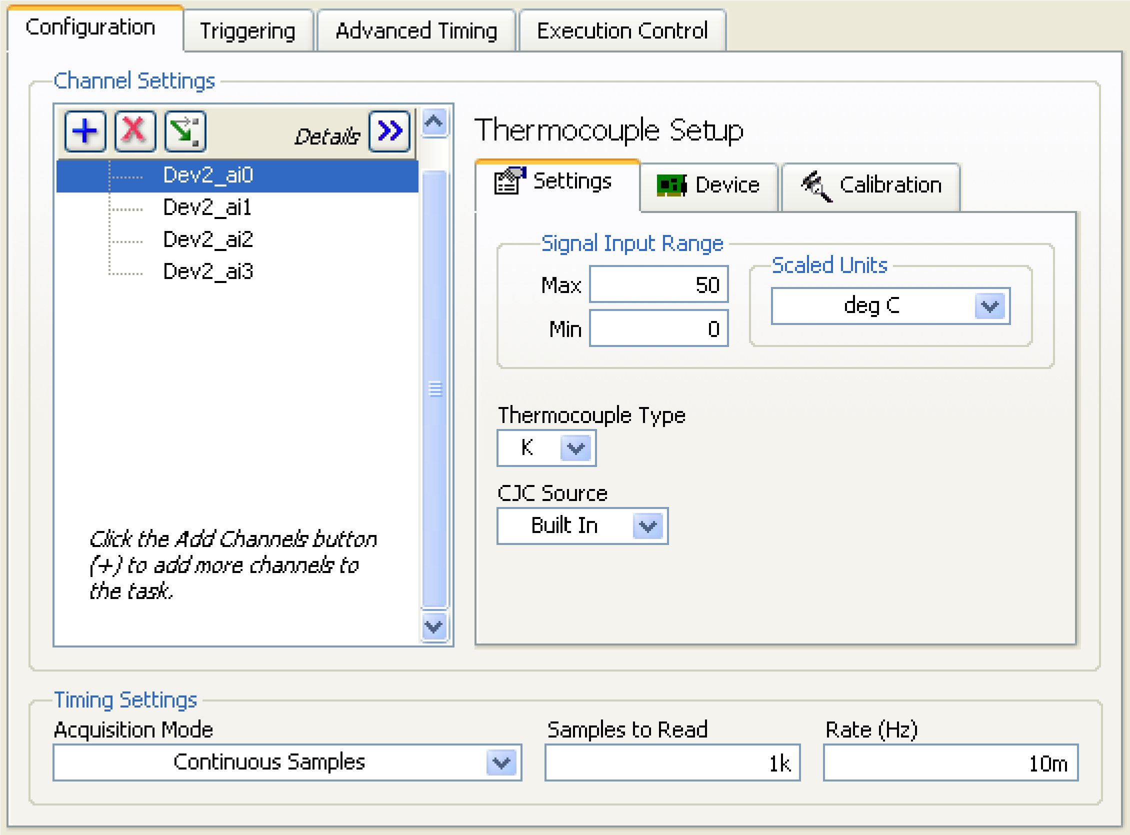


***Figure 35**: Labview Signal Express Thermocouple Setup*

'*Continuous Sampling*' was selected and the '*Rate*' was set to 0.01 Hz. Labview Signal Express recommended setting '*Samples to Read*' to 1000.

Advanced Timing required that the '*Timeout*' between readings be adjusted according to the following equation:

$$\text{Timeout} = \frac{\text{Samples to Read}}{\text{Sample Rate}} \qquad \textbf{(1)}$$

Type K thermocouples were selected and degrees Celsius were chosen as the selected units.

7.163 <u>Humidity Sensor Step</u>

Figure 36 shows the voltage input setup for the humidity sensor and NI USB-6008 device.

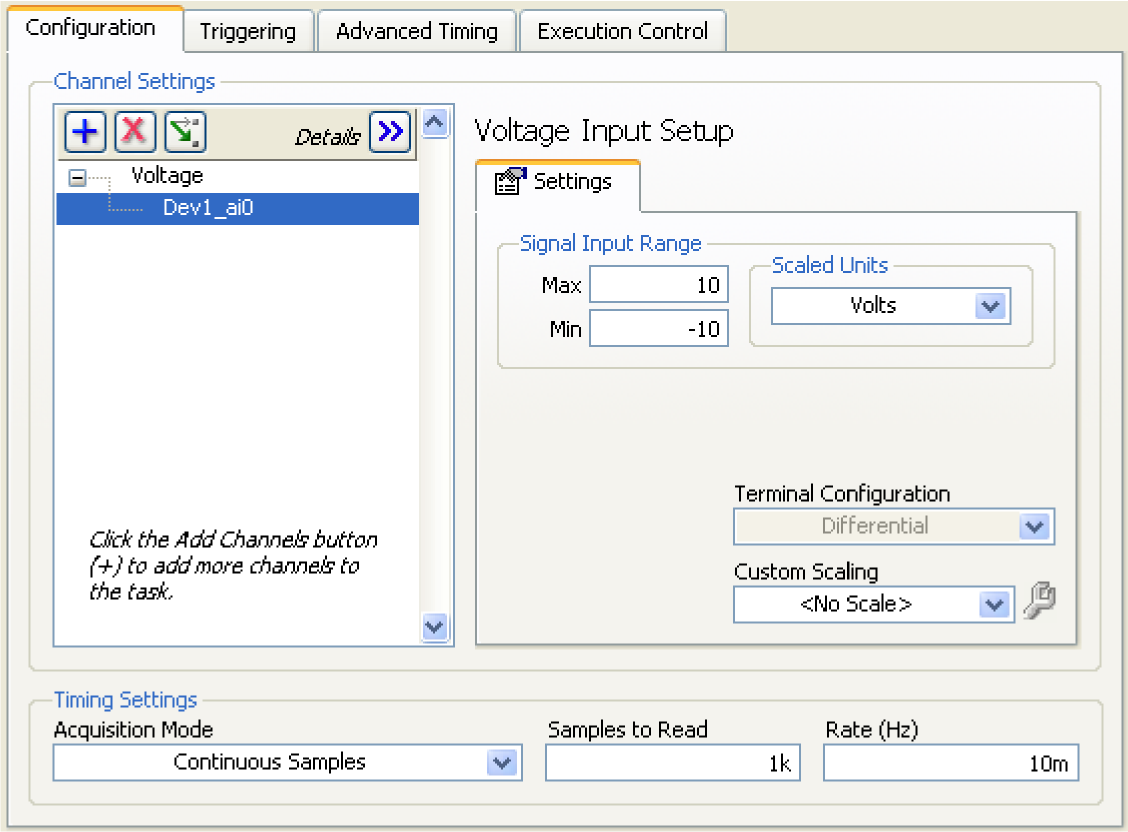


***Figure 36**: Labview Signal Express Voltage Input Setup*

The same timing settings were selected as for the thermocouple setup.

When the two steps had been set up a test run was undertaken to confirm accurate readings were being taken.

The data acquisition system was now setup up and data was ready to be recorded.

7.2 Green Roof Energy Balance

The green roof energy balance for extensive green roofs proposed by Feng et al. [38] is established with the following prequisites:

- The lawn, with 100% leaf coverage, is considered as a diffuse grey body.
- Thermal effects of plants metabolism - except for photosynthesis, respiration and transpiration – and thermal effects of microorganisms in the soil are negligible.
- The conditions with precipitation and dew are not included.
- The green roof is large enough to assume horizontal homogeneity and apply one dimensional (vertical) analysis.

The energy exchange between an extensive green roof and its surrounding environment is illustrated as follows:

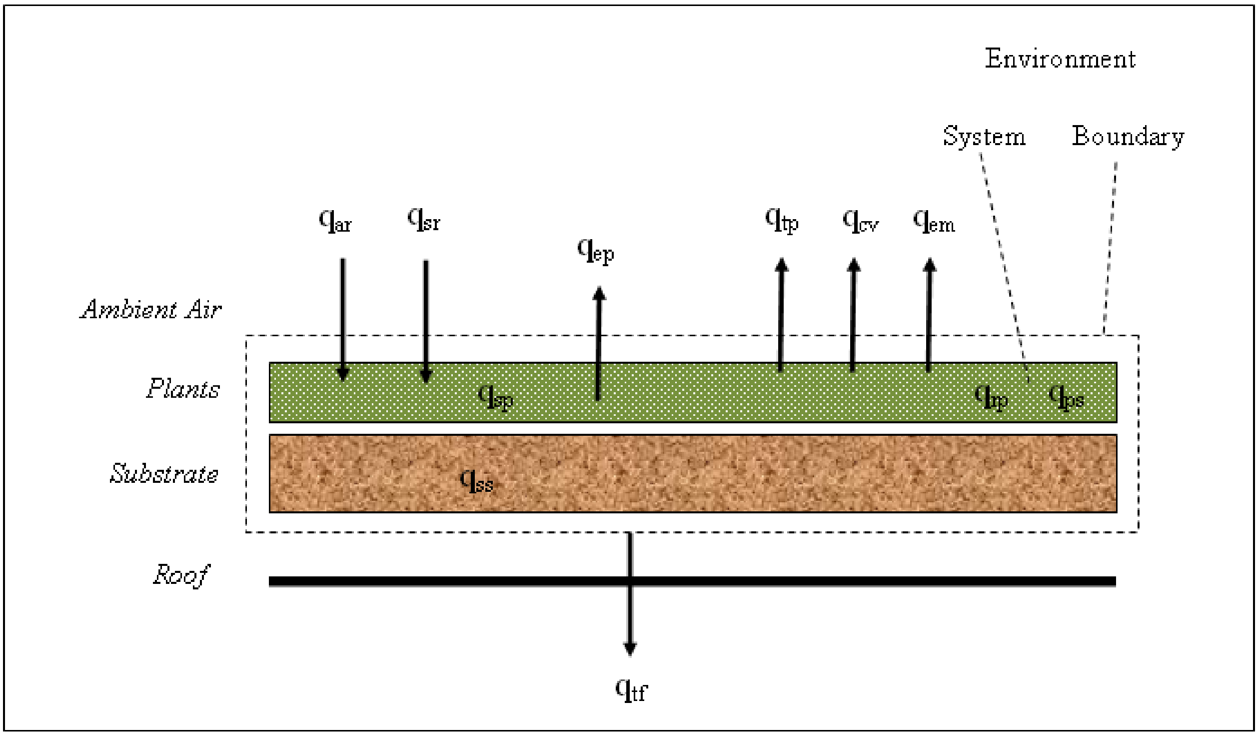


Figure 37: *Energy Exchange between an Extensive Green Roof and its Environment*

Using the first law of thermodynamics, the following energy balance equation is obtained:

$$q_{sr} + q_{lr} + q_{cv} + q_{em} + q_{tp} + q_{ep} + q_{sp} + q_{ss} + q_{tf} + q_{ps} + q_{rp} = 0 \qquad \textbf{\textit{(2)}}$$

Where,

q_{sr} = Heat Gain from Solar Radiation (W/m^2)

q_{lr} = Heat Gain from Long-Wave Radiation (W/m^2)

q_{cv} = Heat Transferred by Convection (W/m^2)

q_{em} = Heat Loss by Emission (W/m^2)

q_{tp} = Heat Loss by Transpiration (W/m^2)

q_{ep} = Heat Loss by Evaporation (W/m^2)

q_{sp} = Heat Storage by plants (W/m^2)

q_{ss} = Heat Storage by Soil (W/m^2)

q_{tf} = Heat Transferred into the Room (W/m^2)

q_{ps} = Solar Energy Converted by Photosynthesis (W/m^2)

q_{rp} = Heat Generation by Respiration (W/m^2)

The vegetation and soil are considered as the system and the structural roof and ambient air as the environment.

The calculation methods for photosynthesis, respiration and metabolism as recommended by Meng et al. [45] and Feng and Chen [46] can be integrated from time τ to time $\tau + \Delta \tau$ to form the following macroscopic energy balance:

$$\alpha_s \int_{\tau}^{\tau+\Delta\tau} q_{sri}\, d\tau + \alpha_l \sigma \int_{\tau}^{\tau+\Delta\tau} (t_a + 273.15)^4 (0.802 + 0.004 t_d)\, d\tau$$
$$+ \int_{\tau}^{\tau+\Delta\tau} (5.7 + 3.8\nu)(t_p - t_a)\, d\tau + \sigma\varepsilon \int_{\tau}^{\tau+\Delta\tau} (t_p + 273.15)^4\, d\tau$$
$$+ l \int_{\tau}^{\tau+\Delta\tau} R_{et}\, d\tau + \rho_p \int_{t_p}^{t_p+\Delta t_p} c_p\, dt_p + \rho_s \int_{t_s}^{t_s+\Delta t_s} c_s\, dt_s \tag{4}$$
$$+ \int_{\tau}^{\tau+\Delta\tau} q_{tf}\, d\tau + \frac{\int_{\tau}^{\tau+\Delta\tau} q_{sri}(\tau)\, d\tau}{\int_0^{24\,\mathrm{h}} q_{sri}(\tau)\, d\tau} \frac{6.5}{TC(1 + (R_{ep}/R_{tp}))} l \int_0^{24\,\mathrm{h}}$$
$$R_{et}\, d\tau = 0$$

Where,

α_s = Shortwave Absorptivity of Green Roof

q_{sri} = Incident Solar Radiation (W/m^2)

α_l = Long Wave Absorptivity of Green Roof

σ = Stefan Boltzmann Constant (W/m^{2}K^4)

t_a = Ambient Air Temperature (^{o}C)

t_d = Dew Point Temperature (^{o}C)

ν = Wind Speed above Canopy (m/s)

t_p = Plant Temperature (^{o}C)

ε = Emissivity of Green Roof

ι = Latent Heat of Vaporisation (kJ/kg)

ρ_P = Areal Density of Plants (kg/m^3)

c_p = Specific Heat of Plants (kJ/kgK)

ρ_s = Areal Density of Dry Substrate (kg/m^3)

c_s = Specific Heat of Dry Substrate (kJ/kgK)

t_s = Soil Temperature (^oC)

q_{tf} = Heat Transferred into Room (W/m^2)

TC = Transpiration Coefficient

R_{ep} = Evaporation Rate (kg/m^{2}s)

R_{tp} = Transpiration Rate (kg/m^{2}s)

R_{et} = Evapotranspiration Rate (kg/m^{2}s)

Of the 19 parameters in equation 2, only q_{sri}, q_{tf}, t_a, t_d, t_p, t_s, ν, R_{et} need to be measured in order to understand the energy exchanges in an extensive green roof. The other parameters are either constants or can be specified according to the real situations.

7.3 Green Roof Test Rig for Rainfall Runoff

A green roof test rig was set up to compare the rainfall runoff of an extensive green roof and a perspex panel (to replicate a PV panel). A 10 degree roof angle was specified for a shallow flat pitch roof. Guttering was placed on the test rig to collect any runoff and this was measured using measuring cylinders.

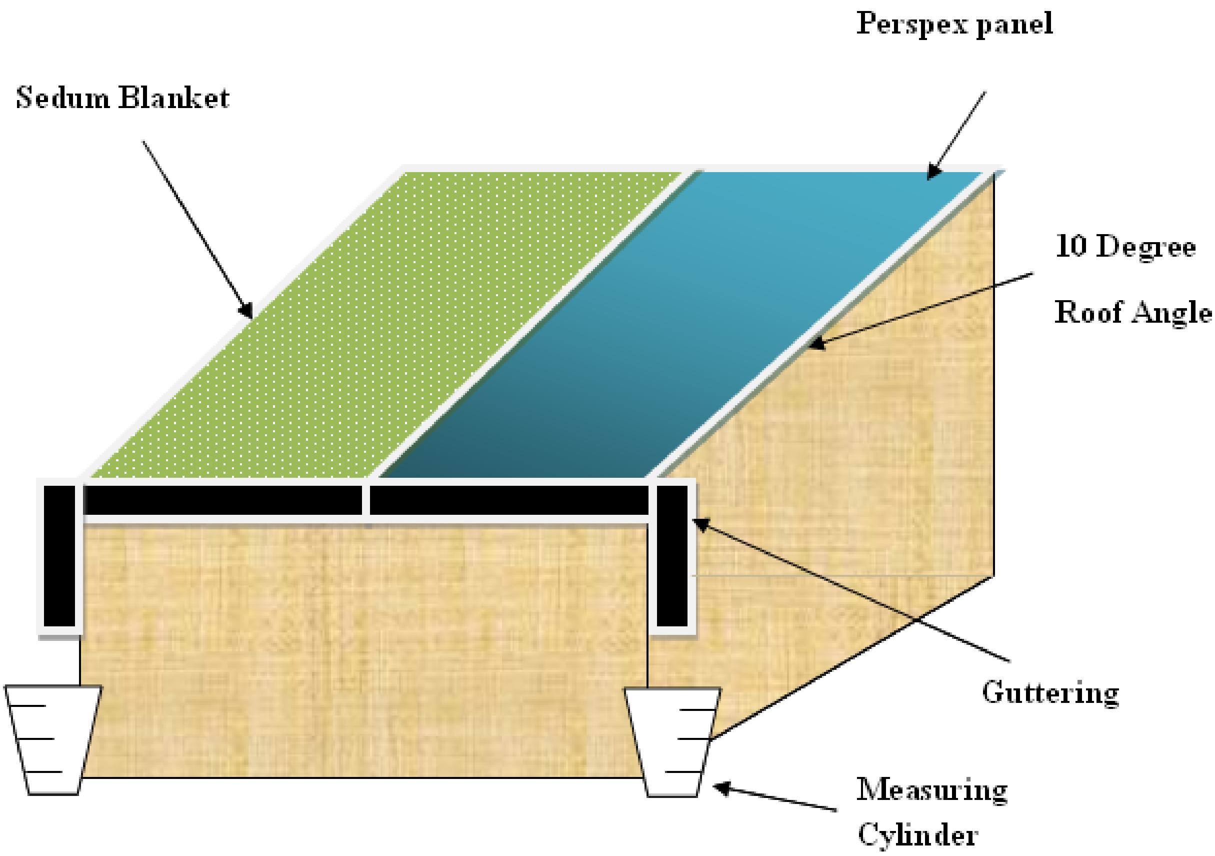


***Figure 38**: Green Roof Test Rig for Rainfall Runoff*

The total area of the roof was 1.2m^2, with one half being the sedum blanket and the other half the Perspex panel. The sedum blanket was placed in an impervious raised frame, which allowed for runoff collection. The same sedum blanket was used as for the thermal performance.

Artificial rains which mimicked individual rain events were applied over the test rig by means of a sprinkler; then runoff volumes were measured at one minute intervals using measuring cylinders. The runoff from the green roof and the perspex panel was compared.

Figure 39: *Green Roof Test Rig for Rainfall Runoff with Artificial Rain Event*

Figure 39 and 40 show the green roof test rig with the perspex sheet

***Figure 40**: Green Roof Test Rig for Rainfall Runoff with Sprinkler*

8 Results and Analysis

The methodology for both thermal and rainwater runoff performance was applied and results were obtained and analysed. As mentioned previously, the thermal performance results were obtained using Labview Signal Express. The rainwater runoff results were obtained manually.

8.1 Thermal Performance

8.11 Test 1

The first test was run for 3 days from the 2nd till the 5th of September – beginning at 1840 hours and finishing at 2140 hours. Figure 41 shows the temperature distribution from various points on the green roof.

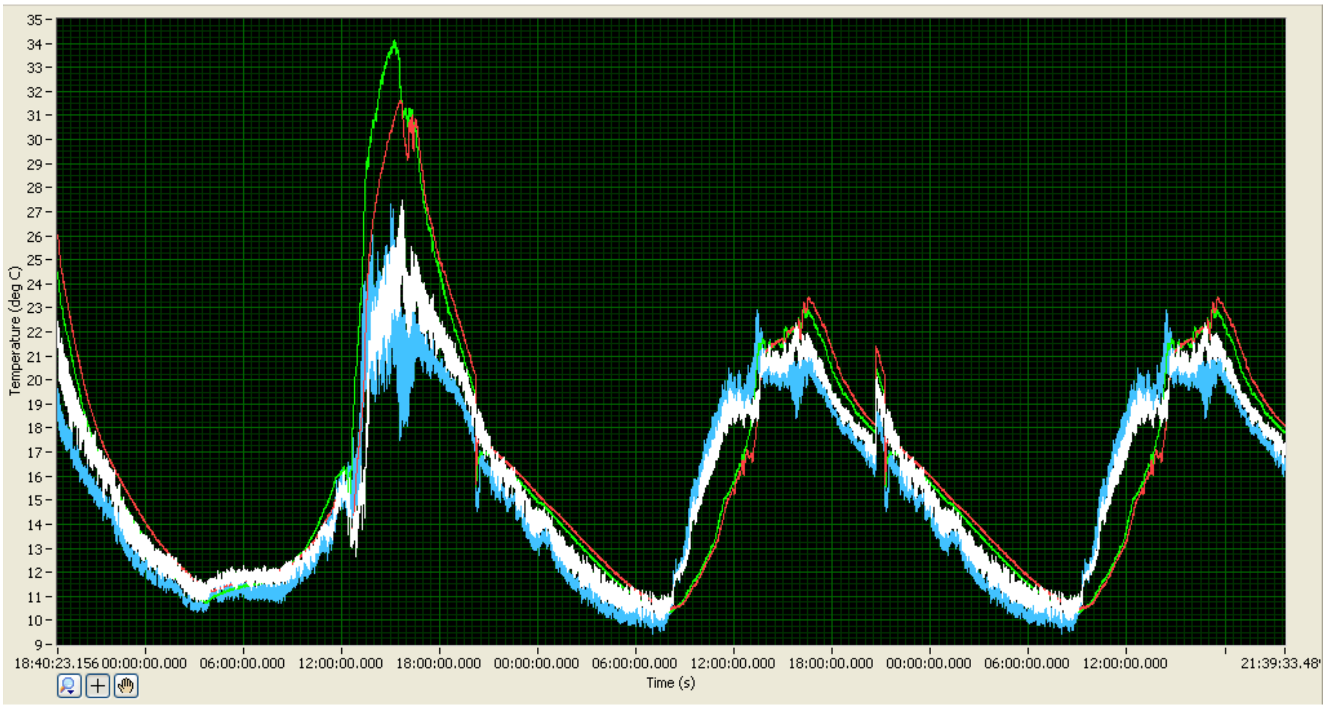


***Figure 41**: Test 1 Green Roof Test Rig Temperatures*

The white line indicates the under roof temperature; red for the substrate temperature; green for the leaf temperature and blue for the ambient air temperature. As can be seen from figure 40, the peak temperature at the vegetation level is 34 ^{o}C and this occurs mid-afternoon on the second day of the experiment. The lowest temperature generally occurs above the green roof – dropping to a low of around 5 – 10 °C on the second and third days.

As would be expected, the highest temperatures generally occur at vegetation level; where the thermocouple is exposed to the sun but is sheltered from the wind. The substrate temperature would be expected to be lower, but a number of factors may explain this such as: the low moisture content (15 – 20 %) during the experiment; the shallow depth of substrate and a high content of crushed brick and clay shale and also the partially developed coverage of the substrate by the vegetation. Over time, as the vegetation layer further establishes, the improved coverage would help to lower the substrates exposure to the sun, hence lowering its temperature.

8.12 Test 2

The second test was run from the 8th – 11th of September – starting at 1840 hours and finishing at 0600 hours. The results can be seen in figure 42.

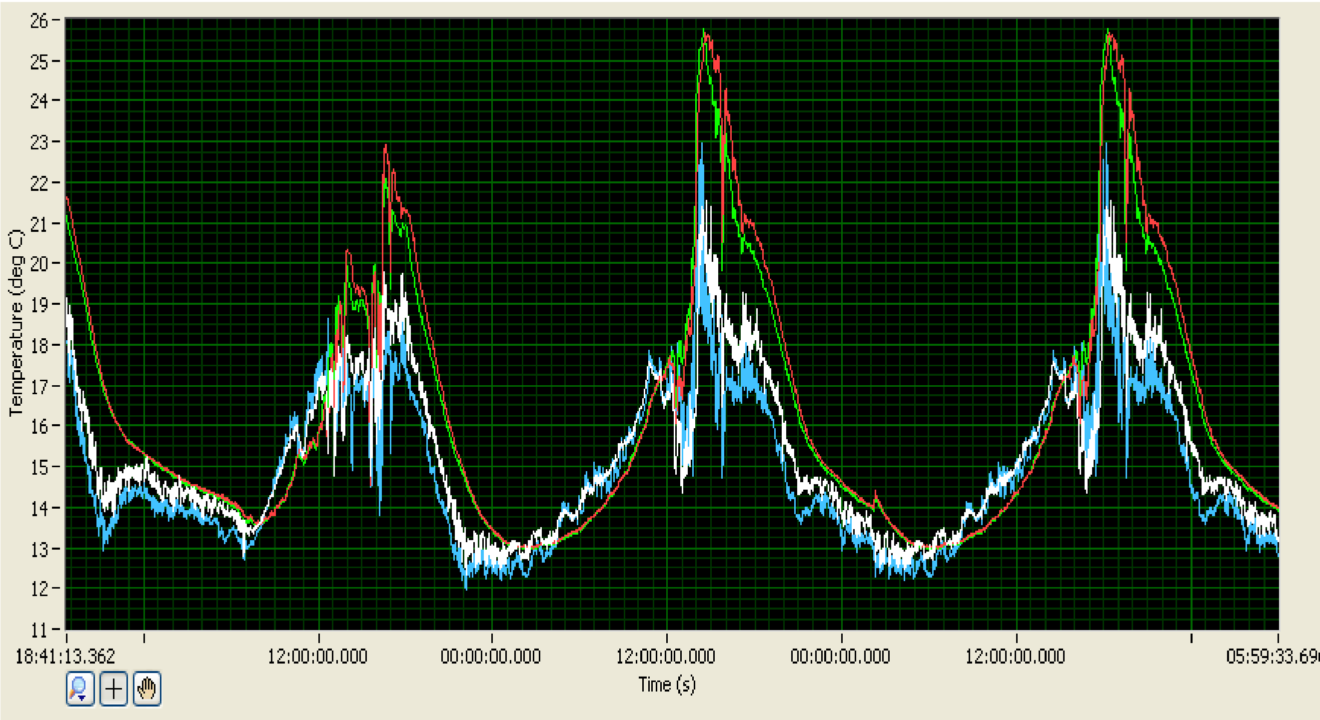


***Figure 42**: Test 2 Green Roof Test Rig Temperatures*

The second test reflects the results of test 1 – showing that the peak daytime vegetation and substrate temperatures (25 – 26 °C) are generally higher than the ambient air and under roof temperatures. A time lag between the cooling of the sedum blanket and the ambient air and under roof can also be seen from figure 41.

The moisture content for test 2 was also 15 – 20 %.

8.13 Energy Balance

Due to the time constraints of the project, an energy balance could not be carried out for tests 1 and 2. The setup required to obtain the additional data for an accurate energy balance (such as incident solar radiation and wind speed above the test rig) were also beyond the scope/time frame of this project.

8.2 Rainwater Runoff Performance

The first artificial rain event was set for an intensity of 1 mm/min and the duration of this was 20 minutes. Therefore the total rainfall was 20 mm.

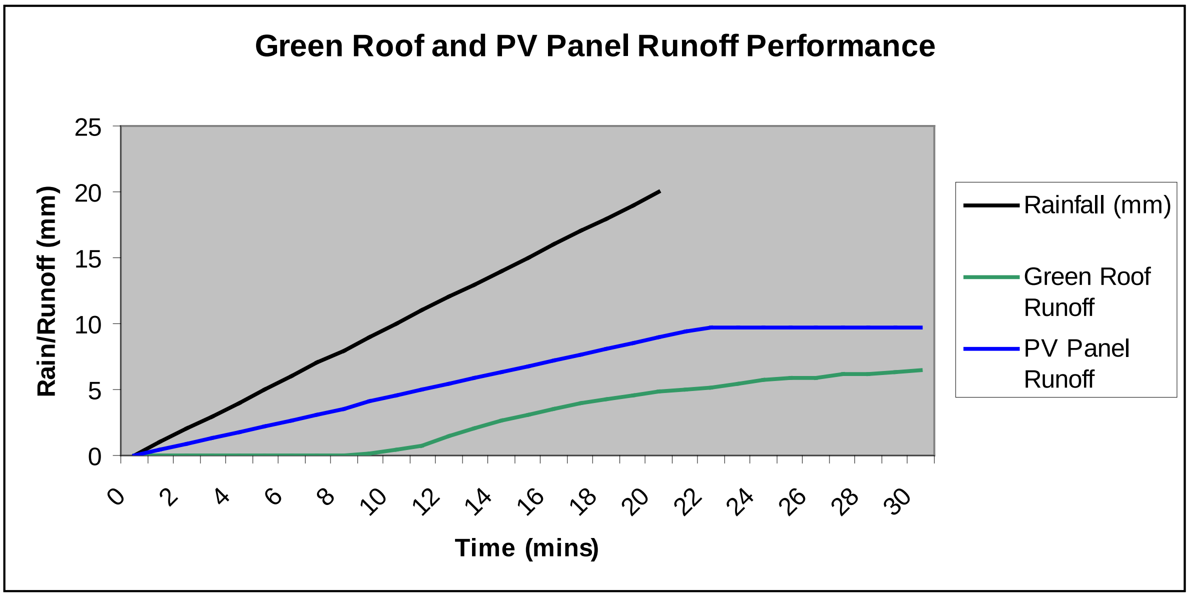


***Figure 43**: Green Roof and PV Panel Runoff Performance for 1 mm/min Rain Event*

As can be seen from figure 43, runoff occurs from the green roof after 9 minutes – requiring 9 mm of rainfall for runoff to occur. Runoff from the PV panel occurs almost immediately with the artificial rain event. When the rain event stops the runoff from the PV panel stops soon afterwards (around 23 minutes), whereas runoff continues from the green roof.

The second artificial rain event was set for an intensity of 2 mm/min and the duration of this was 20 minutes. Therefore the total rainfall was 40 mm.

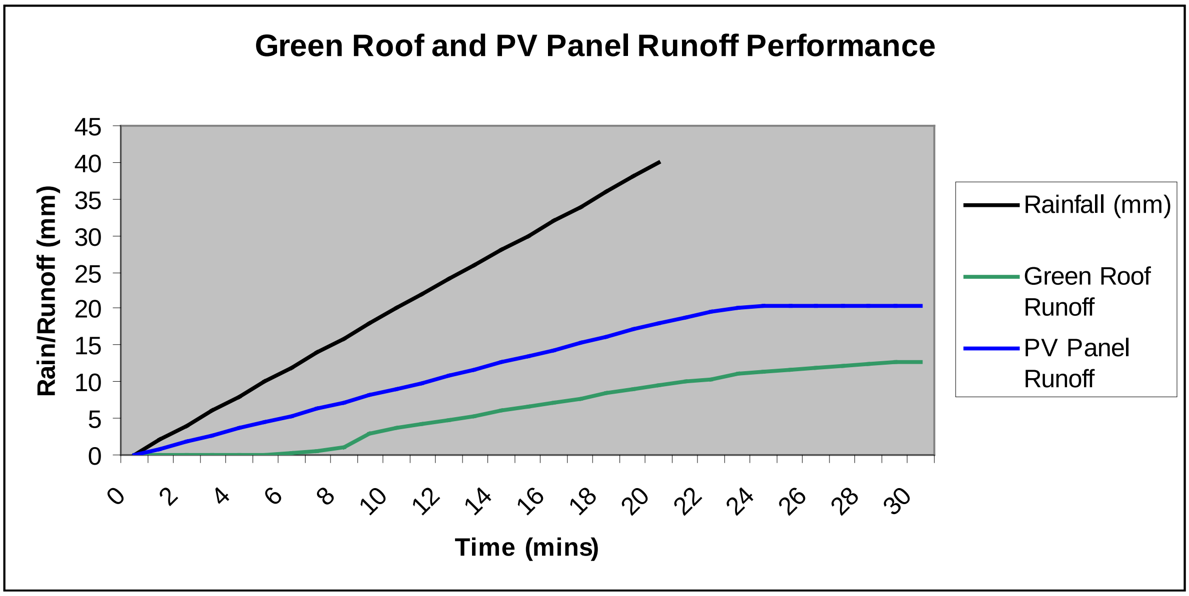


***Figure 44**: Green Roof and PV Panel Runoff Performance for 2 mm/min Rain Event*

As can be seen from figure 44, runoff occurs from the green roof after 6 minutes – requiring 10 mm of rainfall for runoff to occur. Runoff from the PV panel occurs almost immediately with the artificial rain event. When the rain event stops the runoff from the PV panel stops soon afterwards (around 25 minutes), whereas runoff continues from the green roof.

For both rainfall events, the initial moisture content of the substrate was 15 – 20%.

9 Conclusions and Recommendations

9.1 Conclusions

In conclusion, it can be seen the effect that the different layers of the green roof have on temperature. The vegetation and substrate of the sedum blanket absorb and dissipate heat allowing for cooler temperatures beneath the roof. This results in higher temperatures at the substrate and vegetation level compared to the ambient air and under roof temperatures.

In terms of the runoff performance of the green roof in comparison with a perspex sheet (to replicate a PV panel), the sedum blanket delays and reduces the rainwater runoff. For a rainfall intensity of 1 mm/min, 9 mm of rain is required to start runoff. For a rainfall intensity of 2 mm/min, 10 mm is required to start runoff.

9.2 Recommendations

The experimental scope of this project was limited by its timescale and the ability to obtain and set up the necessary equipment/apparatus within this period (and obtain/analyse results). A study for a longer period of time would be required to obtain any conclusive results – but the results from this project show an example of the performance of extensive green roofs.

Research into the thermal performance of green roofs is well established. However, the comparison of rainwater runoff between green roofs and PV panels is an area of research which could further be explored. It is established that the cooling effect of green roofs help to improve PV efficiency, but the evidence from this project suggests that green roofs would also offset the 'poorer' runoff performance of PV panels – an additional benefit. Further research into this on a larger scale, over a longer period of time would provide more conclusive results.

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Appendix 1

BAUDER

Date: 10-04-2010

TECHNICAL DATA SHEET

Bauder Xero Flor XF301 Sedum Blanket

DESCRIPTION
A pre-cultivated vegetation blanket on a patented nylon loop and geo-textile base carrier with substrate growing medium. The pre-attached moisture retention fleece provides some water storage.

TECHNICAL DATA:
Composition

Mineral component	recycled crushed brick and expanded clay shale
Organic component	composted pine bark

Technical Performance

pH value	6.5 – 7
Vegetation support layer	geo-textile carrier filter layer with bonded UV resistant nylon loops
Moisture retention fleece	recycled fibres (80%man-made, 20% organic)

Weights and sizes

Standard roll width	1 metre
Standard roll length	2 metres
Non-standard lengths	up to 10m (cut only in increments of 1m)
Thickness:	ca. 28mm (excluding vegetation)
Saturated weight:	44Kg/m²

Fire Rating

BS 476 Part 3:2004	Ext. F. AA

Supply Form
Rolls of blanket to specified lengths (as above)