The thermal effects of green roofs and walls:

Experimentation on the performance of vegetated building envelopes in the UK

A thesis submitted to the University of Sheffield for the degree of Doctor of Philosophy

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Abstract

Despite a number of previous studies investigating the thermal benefits of green roofs and walls, results were not applicable to all types of climate as the focus was predominantly based on the reduction of cooling loads. Therefore, two separate field experimentations were conducted on green roofs and walls in Meltham and Sheffield to evaluate the thermal effects of vegetation cover on buildings within the UK climate. Temperature measurements of building surfaces and interior space were recorded throughout four seasons, and observation results demonstrated that vegetation reduced daily temperature fluctuations occurring on the building's exterior surfaces. Vegetation was particularly effective in mitigating the influence of solar radiation; both green roofs and walls reduced daily peak temperatures of the building surface by approximately 12℃ during the warmest month. This study also look ed at factors that could influence the performance of vegetation. Increased substrate mass in the green roof improved insulating performance to increase indoor air temperature, meaning that intensive green roofs with a substrate thickness of over 200mm would be suitable in cooler climates, and shallower green roofs with less negative insulating impacts during summer in warmer climates. Only a marginal difference in thermal performance was observed among all tested green walls including three modular living walls and a climber screen, suggesting that choosing systems with the lowest initial costs and maintenance would be beneficial from an economic perspective. Numerical analysis conducted using recorded temperatures found that green walls were more effective in reducing daily heat gain through the wall than heat loss. Although adding a layer of insulation improved the thermal resistance of the existing green wall systems, the comparison against a conventional external insulation material revealed that it was more effective in reducing heat loss through the wall and would be a better solution in heating load dominated climates such as the UK. The study

proved that the true potential of green walls lies in the variable characteristics of such materials in reducing radiation gain during the day but having minimum insulation effects at night. Thus, the greatest thermal benefits of green walls can be achieved in cooling load dominated regions.

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List of abbreviations

BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Methodology
CIBSE	Chartered Institution of Building Services Engineers
CIRIA	Construction Industry Research and Information Association
HVAC	Heating, ventilation and air conditioning
LAI	Leaf area index
LEED	Leadership in Energy and Environmental Design
UHI	Urban Heat Island

List of symbols

Symbol	Unit	Description
T_{in}	℃	Indoor air temperature
T_{out}	℃	Outdoor air temperature
T_{se}	℃	External wall surface temperature
$T_{se,ref}$	℃	External wall surface temperature of the reference wall
$T_{se,green}$	℃	External wall surface temperature behind green wall
$T_{se,green,ins}$	℃	External wall surface temperature behind green wall with added insulation
$T_{se,ins}$	℃	External wall surface temperature behind insulation panel
T_{si}	℃	Internal wall surface temperature
$T_{si,ref}$	℃	Internal wall surface temperature of the reference wall
$T_{si,green}$	℃	Internal wall surface temperature behind green wall
$T_{si,green,ins}$	℃	Internal wall surface temperature behind green wall with added insulation
$T_{si,ins}$	℃	Internal wall surface temperature behind insulation panel
T_{pl}	℃	Temperature inside the foliage of plants
T_{sub}	℃	Temperature inside living wall substrate
H_{ref}	W/m^2	Heat flow through the reference wall
H_{ins}	W/m^2	Heat flow through the wall behind insulation panel
H_{green}	W/m^2	Heat flow through the wall behind green wall

$H_{green,ins}$	W/m^2	Heat flow through the wall behind green wall with added insulation
Solar	W/m^2	Solar radiation
Rt	$m^2 \cdot K/W$	Thermal resistance of a wall
K	$W/m \cdot {}^2K$	Thermal transmittance of a wall
λ	$W/m \cdot K$	Thermal conductivity of a material
T	m	Thickness of a material
Q	W/m^2	Hourly heat flow through a wall
Q_{24}	W/m^2	Daily heat flow through a wall
Q_{load}	W/m^2	Hourly energy load of a wall
$Q_{load,24}$	W/m^2	Daily energy load of a wall
a	W/m2·K	Thermal conductivity of indoor air

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1. Introduction

1.1. Background of the study

Reintroducing greenery to dense urban areas has been part of a strategy used by many local governments around the world to improve city environments. One of the promising options for urban revegetation is greening the surface of buildings. Selectively applying greenery on otherwise hard building surfaces would increase the much needed green mass in cities, linking existing parks and gardens to vegetated roofs and walls, and by doing so creating a seamless semi urban effect. This would be particularly beneficial to inner cities where existing green spaces are rather scarce and very often isolated from one another. The ratio of a citie's vegetation cover can be less than a third of the total surface area compared to 75–95% in the outer suburbs (Greater London Authority 2008; Johnston and Newton 2004).

The true potential of green roofs and walls lies in the use of existing and otherwise unutilised building surfaces. Our working and living areas within the inner city forcibly have to climb vertically as a lack of available land is an ever increasing issue. Conventional urban vegetation such as street trees and courtyard greens are often vying for space with more commercially viable land uses (Dunnett and Kingsbury 2008). By utilising surfaces of buildings, urban canyons offer platforms to grow vegetation limited only by the height of a building being especially useful where land is at a premium (Johnston and Newton 2004). Green roofs can replace the footprint of a building with vegetation and vertical greenery, as Yeang (1996) saw it twenty years ago, has a great advantage to increase vegetated surface areas within a buildings footprint and provide necessary green mass within cities.

Previous studies have found that green roofs and walls can improve a number of different aspects of the urban environment. In addition to the thermal effects which are the focus of this thesis, urban vegetation can provide a living habitat for wildlife and increase biodiversity within a city (Francis and Lorimer 2011). It also creates a better working and living environment for humans by providing place for recreation also enhancing the aesthetics of cityscapes (Lee and Maheswaran 2011; Seymour et al. 2010; White and Gatersleben 2011). Plants purify the air by capturing airborne pollutants (Currie and Bass 2008; Pugh et al. 2012; Speak et al. 2012), and green walls in particular have great potential as they can create a large foliage mass (Joshi and Ghosh 2014). Green roofs and walls have also been included in strategies for storm water management in some cities due to the abilities of vegetation to retain water and reduce peek runoff (Heidt and Neef 2008; VanWoert et al. 2005). A vegetation layer also acts as a filter and improves the quality of runoff (Berndtsson et al. 2006).

Expectations for green roofs and walls as a driving force for urban revegetation are illustrated by the fact that many cities around the world have now introduced their own environmental policies to either promote the technology or make it part of compulsory measures to combat the environmental issues that cities face today. Since 1998, a third of all cities in Germany have established regulations regarding green roofs to help restore ecosystems in urban areas. (Romo 2012). A policy to encourage roof vegetation primarily to reduce the city’s storm water runoff has been introduced in Portland and Philadelphia in the USA, Toronto in Canada and most recently in Copenhagen, Denmark (Ansel and Appl 2010; Grant 2006; Spolek 2008). Cities in tropical and subtropical climates such as Singapore and Tokyo, Japan, where extreme heat and peak electricity demands are a major issue in summer are running programmes related to green roofs and walls as part of their strategies to mitigate the Urban Heat Island (UHI) effects, which is a phenomenon causing warmer temperatures in urban areas compared to surrounding rural areas (Ansel and Appl 2010; Tokyo Metropolitan Bureau of Environment 2008). Sydney, Australia launched a ‘Green Roofs and Walls Strategy’ in 2012 as part of the plan to reduce carbon pollution in the city (City of Sydney 2012). In the UK, the first policy regarding green roofs and walls was established in 2008 following the publication of a technical report with installation guidelines established by the Construction Industry Research and Information Association (CIRIA). The policy was part of the ‘London Plan’, a spatial development strategy, addressing issues of climate change adaptation and biodiversity promotion, implementing requirements for incorporating green roofs or walls on new building developments in London’s central activity zones (Greater London Authority 2008, 2011).

The multifunctional nature of urban vegetation and the political incentives for installation have resulted in increased areas of green roofs and walls across such pioneering cities and the amount of research and the publications focusing on environmental and social benefits has also increased in recent years (Köhler 2008; Suzuki 2008).

Among the potential economic impacts, the thermal effects of green roofs and walls on buildings often become a focus of debate simply because potential energy savings are one the most quantifiable benefits which can support the dissemination of the technology by providing a clearer idea of how we can offset the often high initial and maintenance costs. With consideration to the installation costs which can average £120–140/m^2 for semi-intensive and intensive green roofs (Greater London Authority 2008) and anything between £150–500/m^2 for green walls (Ottelé 2011; Scotscape Ltd. 2009), as well as the post-installation maintenance expenses, has created much debate. Some argue it would be better to insulate buildings using simpler and more economical methods rather than growing plants on an unconventional surface. However, existing field studies on the thermal impacts of vegetated envelopes, particularly with regards to green walls, are concentrated in climates with a higher temperature and much higher solar radiation exposure compared to the UK (Safikhani et al. 2014), and coherent knowledge and physical data are still lacking to evaluate year-round thermal benefits of vegetation systems in regions where heating loads are a dominant factor.

1.2. Research objectives

The primary objective of this research was to quantify the effects of green roofs and walls on the thermal performance of building envelopes throughout four seasons in the UK climate, including currently limited data for cold periods of the year. Key research objectives are as follows.

1) Quantify the effects of green roofs and walls on the thermal performance of buildings throughout four seasons in the UK, including the impacts on:

- Roof and external wall surface temperatures (Chapter 4 and 5)
- Indoor air temperature (Chapter 4 and 5) and internal wall surface temperature (Chapter 5)
- Heat flow through the wall (Chapter 6)

2) To identify factors that influence the thermal performance of green roofs and walls including:

- Thickness of a green roof substrate (Chapter 4)
- Presence of plants in green walls (Chapter 5 and 6)
- Added insulation layer to increase thermal resistance of green walls (Chapter 5 and 6)
- Type of green wall system (Chapter 5 and 6)

3) Investigate the effectiveness of green wall systems as a building insulation material in the UK climate with consideration of:

- Performance compared to conventional insulation material (Chapter 6)

- Potential energy savings (Chapter 6)
- Environmental impact of green wall irrigation (Chapter 7)

1.3. Research methodology and thesis outline

The methodology used in this research is mainly empirical, with quantitative data collection through field experiments to quantify the thermal impacts of different types of vegetation system on an actual building. A numerical approach was also employed to evaluate a green wall's performance as an external building insulation material; as part of this assessment, the environmental impacts of irrigation consumption for a green wall's maintenance were also investigated by taking field measurements.

Recommendations to optimise the thermal benefits of green roofs and walls were made on the basis of findings from each study. Figure 1.1 presents the structure of the research and a brief description of chapters within this thesis and are as follows.

Chapter 2 explains the classifications of green roofs and walls used in the industry and the characteristics of the various systems; it also describes how these system variations are relevant to thermal studies carried out for this research.

Chapter 3 presents a critical literature review of existing studies and knowledge in regard to the thermal impacts of green roofs and walls on buildings and describes how they became the basis for the development of this study.

Chapter 4 explores the impacts of green roofs on building thermal conditions within the UK climate by explaining field experimentation conducted on a green roof with a focus on the influence of various substrate thicknesses on the performance of vegetation.

Chapter 5 evaluates the effects of four different types of green walls including the resulting wall surfaces temperatures and the ambient temperature inside a building in the current UK climate by demonstrating results and analyses of data collected during a twelve-month field experiment.

Chapter 6 investigates the performance of green walls as a building insulation material, by calculating heat flow through a wall and energy load using temperature data collected in a field experiment introduced in Chapter 5.

Chapter 7 assesses the environmental impact of irrigation for the maintenance of tested green wall systems which could potentially offset the thermal benefits of vegetation by evaluating the data collected for water consumption and the excess drained from each system.

Chapter 8 summarises the key findings of the studies, addresses its limitations and gives recommendations for future research.

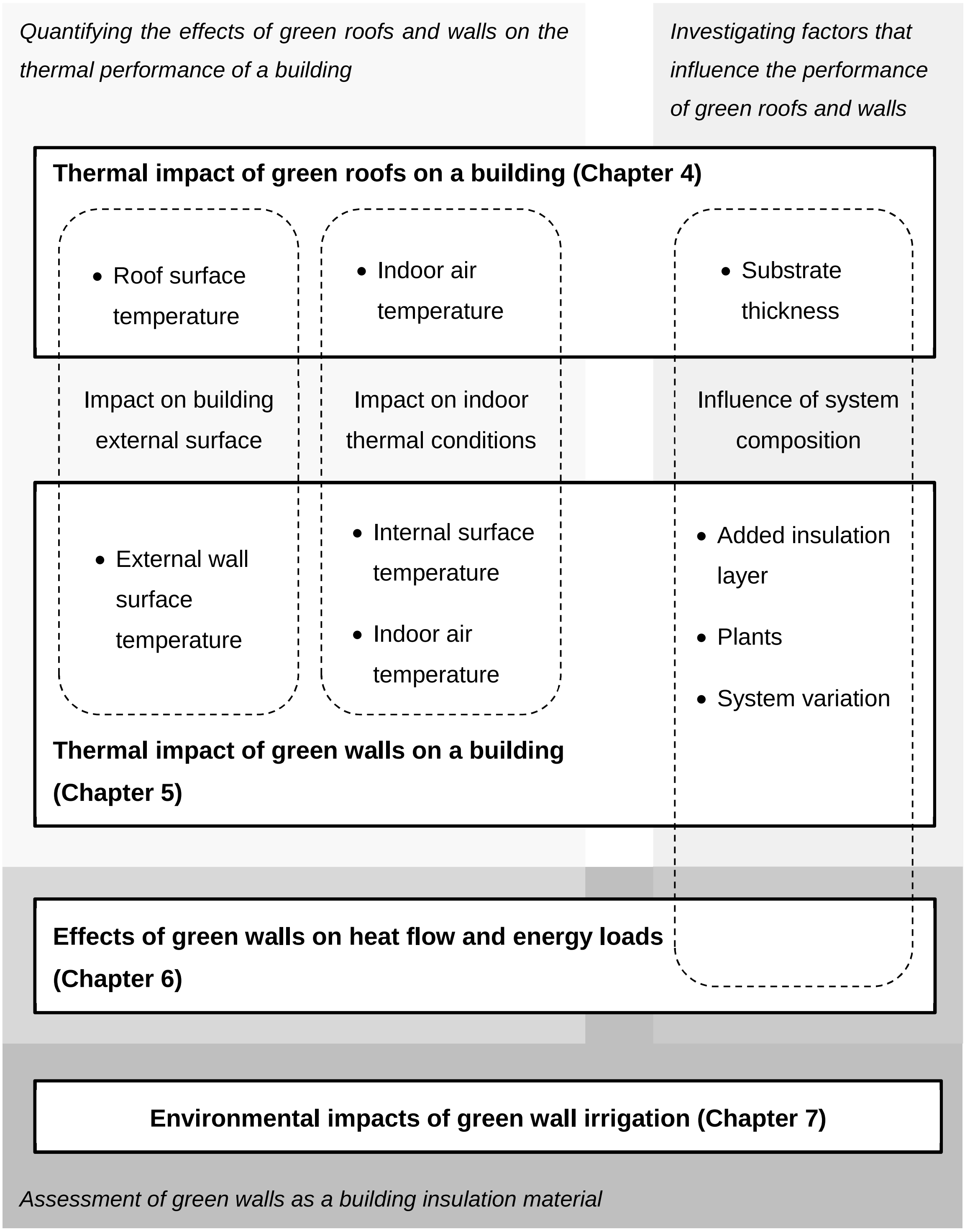


Figure 1.1 Structure of the research

2. Classification of building integrated vegetation

Since the principal focus of this thesis was to investigate the influence of system variations on the thermal performance of green envelopes, the classifications of green roofs and walls used and the characteristics of varied systems currently available within the industry are explained in this Chapter. Firstly, the definition of green envelopes is described in Section 2.1. The basis of classification for green roofs and walls as well as configurations of vegetation systems in each divided category are explained in Section 2.2 and 2.3. Section 2.4 summarises the chapter and also describes how those system variations are relevant to thermal studies carried out for this research.

2.1. Definition of green roofs and walls

A 'green roof' is a vegetation layer installed on a building roof surface comprising of a loose layer of protection materials and growing medium to support plants or by using pre-constructed modular units to create the desired surface area of vegetation cover. Green roofs are constructed for numerous purposes, such as to accommodate recreational areas where space is limited and often to provide specific environmental benefits. Green roof plants are grown in a range of substrate material compositions and depths, depending on the type of vegetation required to achieve the desired effect which can vary from flowering bulbs to few-meter tall trees depending on the maximum load the roof will accommodate. In various international guidelines, green roofs have been categorised as either 'extensive' or 'intensive' mostly dependent on thickness of the substrate layer. Intensive green roofs have traditionally been designed as 'garden roofs' consisting of a thick layer of substrate to create accessible outdoor space in built-up urban areas for people to use, and extensive green roofs as lightweight vegetation cover for other purposes than that of public amenity spaces. However, as the use of green roofs has become wider, the boundaries between those roofs have become less distinct; also classification of green roofs has become more detailed. For example, green roofs are divided into seven different categories in the first green roof guidelines published in the UK, including four types of extensive roofs, two intensive roofs and a 'semi-intensive' roof which consists of a substrate layer of the thickness in-between those two roofs. Their classification was based on the characteristics of the roof such as material make up and thickness of growing medium and the ultimate purpose of the installation (Grant 2006; Groundwork Sheffield 2012).

The term 'green wall' is used for vegetation grown on a vertical surface of a structure including internal and external walls of a building or in some cases, a freestanding wall. Covering the vertical surfaces of a wall was traditionally achieved by encouraging self-climbing plants to spread on a structure, and this simple technique has been used over centuries in many countries to introduce greenery on otherwise hard bare surfaces. Within the more recent trends of vegetated wall applications, contemporary practices have been developed to utilise the building surface as a foundation to grow plants. Modern techniques for integrating vegetation to a vertical building surface are divided into two major categories. 'Green façade' inherited conventional way of using climbing plants to provide green cover on a wall; plants can be either grown directly on a vertical surface or along supporting structures such as wires and trellises. 'Living walls' provide more contemporary methods using specially designed units incorporated into the wall structure to support plants in selected growing mediums. This type of green wall uses multiple containerised planting systems which usually comprise of plants, growing medium, irrigation and drainage.

The range of plants that can be used on green façades are limited as they need to have natural climbing abilities. A wider variety of plants is used on living walls, often herbaceous and small shrubs (Dunnett and Kingsbury 2008; Manso and Castro-Gomes 2015).

2.2. Classification of green roof

Although more detailed classifications are used in some cases, in this thesis, green roofs are divided into the following three major categories recognised by international green roof industry organisations based on their depth of growing substrate.

- Extensive green roof
- Intensive green roof
- Semi-intensive green roof

The standard green roof consists of a growing medium for plants, drainage layer and roof surface protection layer. The figure below shows a typical construction profile of a green roof. Plants can be grown on the roof by sowing seeds on a growing medium onsite, or using pre-grown vegetation mats. These mats usually come in rolls similar to turf and can provide instant green cover on the roof. Sedum and meadow flowers are commonly used species as they are relatively easy to care for with little intervention needed. On some roofs, native species of plants are deliberately selected to support local wildlife.

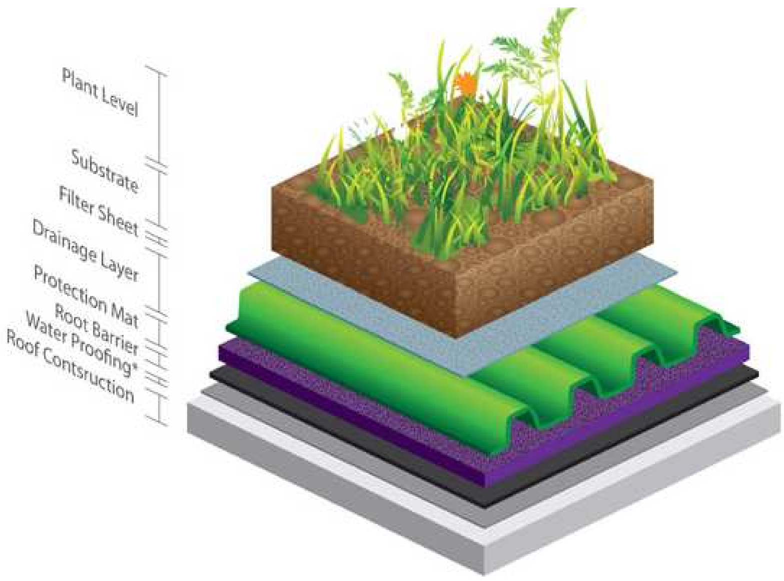


Figure 2.1 Standard construction of a green roof (Groundwork Sheffield 2012)

The growing medium for green roofs is normally a combination of organic matter and other appropriate materials to aerate the substrate such as crushed bricks. The makeup of a medium substrate varies depending on the type of plants to be grown, and the deeper the substrate is, the more diverse species a green roof can support.

When selecting a type of green roof, consideration is often given to the building structure (as saturated substrate can weigh a significant amount), micro climate as well as the purpose of installation in order to seek the best solutions for individual projects. As with any type of vegetation, green roofs require adequate solar exposure, irrigation, drainage and nutrients for the plants to thrive, thus, all green roofs require regular maintenance to ensure the long-term success of any installation (Newton et al. 2007; Peck et al. 1999).

Extensive green roof

An extensive green roof consists of a shallow layer of substrate, usually less than 100mm thick. As it contains a low level of nutrients, hardy plants that do not require much care or water are often used. For example, low-growing succulent plants with the most common species being sedum. This is an economical and low-maintenance type of green roof and widely used to improve local biodiversity by providing habitat for wildlife. Such types of roof are also known as ‘biodiverse roofs’ and usually have limited public access (Groundworks Sheffield 2014).

Intensive green roof

An intensive green roof consists of a deeper layer of substrate over 200mm to support a variety of plant species. This is a high-maintenance roof requiring regular maintenance and a significant amount of irrigation compared to extensive roofs. Due to the heavy weight construction, they are usually built on roof structures with considerable load capacity. They are often incorporated on buildings to create recreational spaces for occupants where space for conventional vegetation is limited. This type of roof is often referred to as a ‘roof garden’ and requires a particularly high level of maintenance to sustain the aesthetic value of such communal roof areas.

Semi-intensive green roof

A semi-intensive green roof is the intermediate of extensive and intensive roofs with substrate depths ranging between 100mm to 200mm. The choice of plants the roof can support becomes larger as the depth of growing medium increases including shallow rooting plants to small shrubs. It can be designed as either a medium or low maintenance roof depending on the type of plants chosen and local climatic conditions.

Figure 2.2 Intensive (garden) roof with trees and shrubs providing a recreational area for office workers (left). Mixture of extensive and semi-intensive green roof designed to promote biodiversity (right). Both green roofs were installed on a high-rise office building in London. (2010)

2.3. Classification of green walls

Similar to green roofs, the distinction among green wall systems can be blurred in some cases and also the terminology for vegetated vertical surfaces is not standardised where terms such as ‘bio-walls’, ‘vegetated walls’ and ‘vertical gardens’ are widely used in the industry.

In this thesis, green walls are divided into two major categories—green façades and living walls; both categories are further divided into three separate classifications based on plants and configuration of the supporting system used as illustrated in Figure 2.3.

Green façades are further divided into three categories according to the mechanism of plants to spread foliage vertically, and the three subcategories for living walls are defined by the design of system components used to encase the growing medium in order to create a layer of substrate on a vertical surface. A brief comparison of the characteristics of each system is explained in Table 2.1.

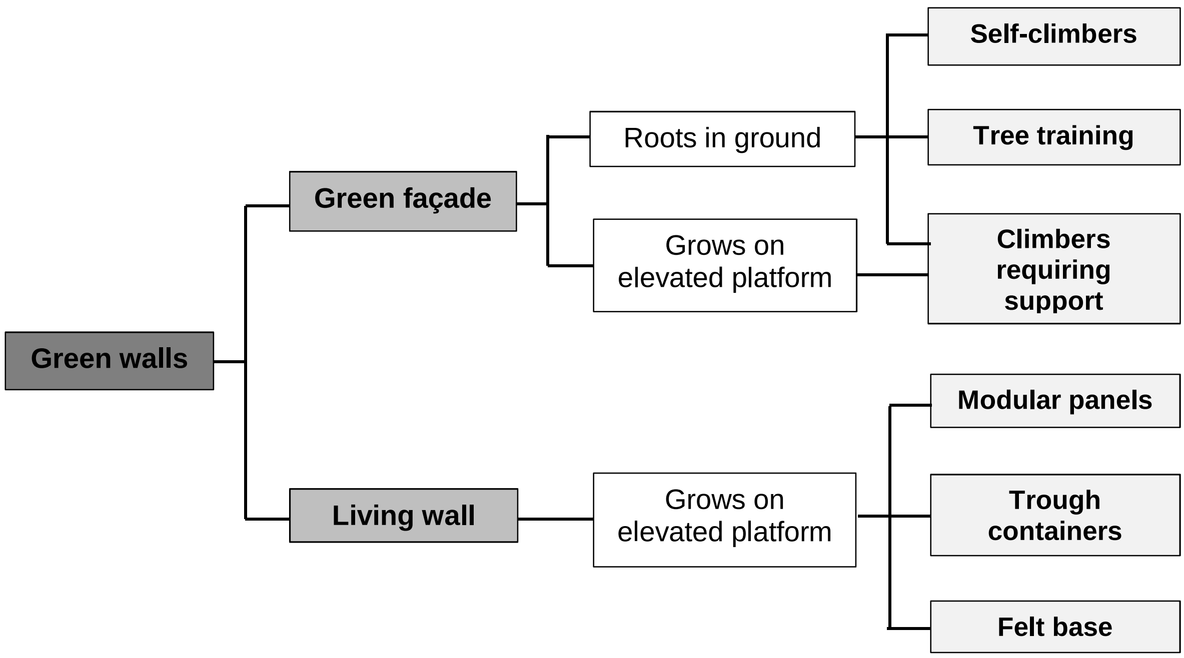
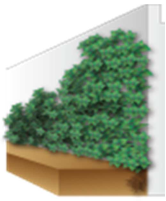
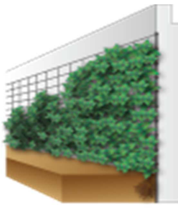
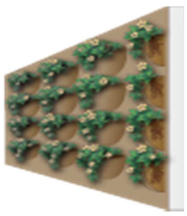


Figure 2.3 Categorisation of green wall systems

Table 2.1 Types of Green wall systems and descriptions of each system

Green façade	
	**Self-Climbers** A system using self-climbing plants such as ivy which directly covers the building surface without any supporting structure.
	**Tree training** A method to train branches of trees to grow along the wall surface using wires and brackets.
 	**Climbers requiring support** A system using supporting material (wire, wire mesh, coconut fibre etc.) to establish foliage cover of climbing plants rooted either in the ground or a container on elevated platform.
Living walls	
	**Modular panels** A system consisting of modular panels encasing selected growing medium. The panels are mounted on the wall structure to create seamless vegetation cover.
	**Troughs** A system incorporating rows of troughs vertically stacked and mounted on a wall. It can accommodate a larger mass of substrate, allowing the support of various species of plants.
	**Felt base** Large sheets of horticultural felt fixed to the wall surface which creates the continuous growing medium and allows random patterns of plants. Highly designed walls are often used as architectural feature.

Initial installation costs and maintenance requirements vary widely depending on the type of plant, green wall system used and growing conditions. The species of plants each system can accommodate and the visual outcome after installation are also different. Table 2.2 shows a comparison of factors with regards to the installation and maintenance of each green wall system highlighting both the merits and disadvantages of each system.

Table 2.2 Comparison of installation and maintenance considerations of different green wall systems

	Type of green walls	Installation cost*	Speed of coverage	Diversity of plants	Maintenance*	Irrigation requirements
Green façade	Self-Climbers	Low	Medium	limited	Low	Low
	Tree training	Low	Very slow	limited	Low	Low
	Climbers with support	Medium	Medium / Fast (Pre-grown)	limited	Low /Medium	Low
Living walls	Modular panels	High	Fast (Pre-grown)	Good	high	High
	Troughs	High	Fast (Pre-grown)	Good	high	High
	Felt base	High	Medium	Very good	high	Very high

*The cost of installation and maintenance reflects on the accessibility of the wall.

In general, more elaborate systems which can accommodate a large variety of plant species and provide a high visual impact come with higher installation costs and also require a higher level of maintenance (Ottelé et al. 2011).

Maintenance requirements for green walls include irrigation and feeding, pruning, clearing of unwanted build ups (old leaves etc.) and pest control (Weinmaster 2009). Living plants require adequate water and nutrients to survive, neither of which can easily be accessed on a high vertical surface, and thus, all green wall systems installed on an elevated platform above ground need regular irrigation and feeding. Irrigation failure will always result in unsuccessful green walls, and an infamous example of this was the UK's first living wall installed at Paradise Park in Islington, London in 2006 where all the plants died within three years of installation due to the lack of design consideration for irrigation (Groundwork Sheffield 2012). In general, green façades require less water as they are either planted in the ground or in a container with a large substrate mass which can collect and retain rain water. Being that watering and feeding are vital for living wall installations, automated irrigation systems are usually incorporated into large-scale projects which can influence the environmental cost for this type of green wall. The required irrigation rate for a wall also varies depending on climatic conditions and orientation of the wall. Green walls need sufficient exposure to the sun as less than four hours of sunlight during the day will increase the probability of plants failing; hence, vegetation is often installed on east to west facing surfaces and the level of solar radiation received on these walls determines the amount of irrigation required (Manso and Castro-Gomes 2015). On commercial green walls, pruning is normally carried out twice per year in order to maintain the appearance of the wall. This is particularly important on walls using climbers due to their vigorous growth. As green façades do not require a high level of irrigation, maintenance is mostly down to pruning (Scotscape Ltd. 2009).

2.3.1. Green façades

Green façades are a method of covering vertical structures with climbing plants or trained shrubs. Plants are grown either by exploiting their self-climbing mechanisms or with the aid of various support systems. In this thesis, green façades are divided into the following three different categories based on the mechanism of plants to establish foliage cover on a vertical surface.

- Self-climbers
- Climbers requiring support
- Tree training

Tree training is a traditional method of growing small trees and shrubs two-dimensionally against vertical structures. Plants grow in the ground in front of the structure and branches are trained along the vertical surface. In Western Europe, the method has commonly been used on the south facing surfaces of a building to grow fruit trees utilising the warmth of the wall, as well as maximising limited land space to create an ornamental wall. As this is a traditional discipline in landscape gardening, this section focuses on the other two techniques used in contemporary green façade practice utilising climbing plants.

Figure 2.4 A pear tree trained at the front of a house (2010)

Climbing plants used in green façades can be classified into two categories including ‘self-clinging climbers’ and ‘climbers requiring support’ depending on the basic mechanisms relating to how they spread foliage upwards along vertical surfaces. The latter is further divided into three separate subcategories based on the way vines are attached into a supporting structure (Figure 2.5).

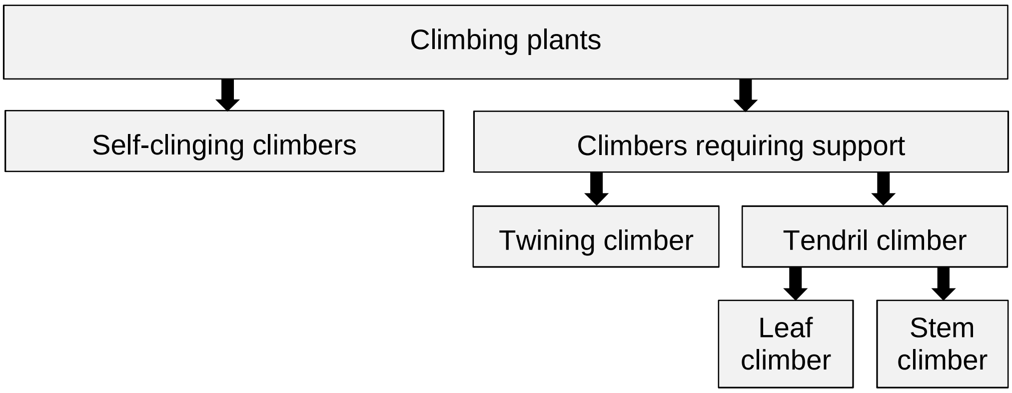


Figure 2.5 Classification of climber plants based on their climbing mechanism (Source: Ottelé 2011)

Self-clinging climber

Figure 2.6 Self-climber cover on a building of the University of Sheffield (right) and a close up image of young ivy vines (left) (2009)

Self-climbing plants have the ability to adhere to the wall surface without any aids. There are a number of self-climbers suitable for green façades and the most common species include ivies, Virginia creepers and climbing hydrangeas. Such plants can grow to a height of 30 meters and cover 600m^2 if undisturbed (Dunnett and Kingsbury 2008).

These plants physically support themselves on vertical structures by directly attaching their roots to the surface using small suction pads. The strength of suction is greatly affected by the type of building surface. Ideally it should have a similar texture to that of a tree trunk or rocks on which climbers are best suited to grow on so that the microscopic root hairs can cling onto the surface (Perini et al. 2011). One of the modern techniques to encourage the rapid growth of self-climbers and more importantly to control the area of green coverage is to provide rough surfaces to assist development, and panels made of fibrous material are often used for this purpose.

Figure 2.7 The green façade of the Chikusa theatre in Nagoya, Japan. Panels made of wire and fibrous foam are mounted on the external walls to ensure sufficient foliage cover across the three-story building (2012)

Climbers require supporting structures

Climbing plants that require supporting structures are divided into two types, twining climbers and tendril climbers.

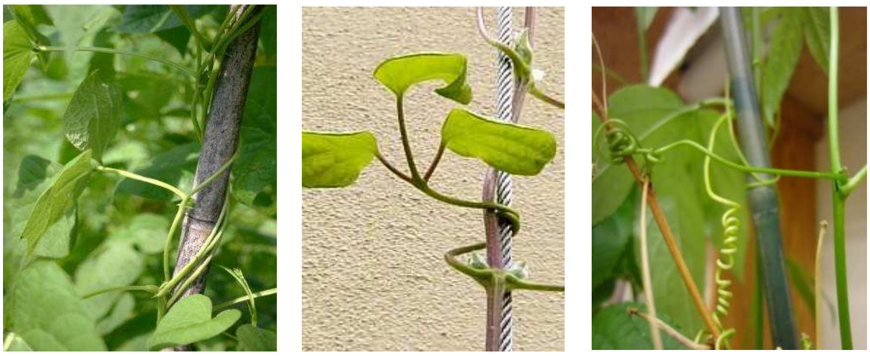


Figure 2.8 Images of twining climber (left) and two types of tendril climbers including leaf climber (middle) and stem climber (right)

Vertically tensioned wires are used for twining plants which develop foliage by twining stem tips in a rotating movement around long thin vertical objects. Supporting wires are often installed away from the wall surface to allow space for the circulating movement of vine plants. Twining plants form the largest group of climbers and commonly used species include Jasmin, wisteria and vines.

Trellises and metal grid panels are often used in green façades for tendril climbers. These plants have either leaf stems (leaf climbers) or specialised stems (stem climbers) which twist in a helical motion to wrap themselves around any supporting structure (both horizontally and vertically) within their reach. This type of climber is mostly deciduous and includes passion flower and clematis (Dunnett and Kingsbury 2008; Grant 2006).

Self-climbing species are also used in ‘green screens’ which is a simple way to provide an instant green cover. The screens usually consist of evergreen ivies planted in a container filled with substrate with foliage pre-grown over integrated supporting materials such as metal wire grid panels to aid plant growth and create a stable screen.

Figure 2.9 Twining climber, morning glory, grown around a vertical wire support structure on a building in Yokohama, Japan (left) and 'green screen' with pre-grown ivy on trellises (right) (2013)

2.3.2. Living walls

Living wall is a technique to cover vertical surfaces with plants that are rooted within a medium incorporated into a walls structure. Although plants seem to stretch horizontally in mass, they usually grow vertically in support mediums such as panels of small containers or water retaining mats attached to or integrated into the wall structure. It is a relatively new practice in wall greenery although there has been a rapidly growing interest as living wall systems can accommodate a larger variety of plant species compared to green façades and create highly attractive living features in contemporary architecture.

In this thesis, living walls are divided into the following three categories based on the design of system components to encase growing substrate in order to create a continuous vegetation layer over a vertical surface.

- Modular panels
- Trough containers
- Felt based systems

Modular panel system

A modular panel system is a combination of flat substrate units and irrigation equipment. The units are mounted on vertical structures to provide a foundation for plants to grow upwards. Modular systems have the advantage of saving construction time and costs, and also reduce the time required for maintenance as it is divided into small individual sections. Each unit encases a preselected growing medium which includes compost and aerating material such as crushed bricks (compost based system) and horticultural mineral wool panel (hydroponic system). Compost based systems usually consist of modular panels with small pockets designed to hold an organic growing medium and plants take root in these compost filled 'cells'.

Figure 2.10 A 170-meter long living wall at Westfield Shopping Centre in London made up of more than 5,000 compost-based modules and 200,000 individual plants (left). Sectional drawing of a typical modular panel encasing organic substrate in individually divided cells (right)

A type of modular panel cladding system which supports plants by water retained in the mineral wool material instead of conventional soil-based growing medium is largely referred to as a ‘hydroponic’ living wall. Panel casings can be made of either plastic or soft irrigation felt which encloses horticultural Rockwool for plants to root in, and individual plants grow in circular pockets created in a rock wool panel.

Figure 2.11 Hydroponic living wall installed at Edgware Road Tube Station, London with 14,000 plants of 15 different species (left) (Biotecture Ltd 2014) and components of hydroponic living wall panels (right) (2011)

Trough container system

The system is designed using planting troughs stacked on top of each other. A unit can be utilised as an individual trough or a row of troughs to form a deep panel unit. Each trough can hold a substantial amount of organic growing medium and plants can spread roots freely inside them, allowing the system to support a wider variety of plants compared to modular panel systems.

Figure 2.12 Trough system installed on the Palace Hotel in Victoria, London, consisting of 16 tons of compost accommodating 10,000 plants (left) and sectional drawing of a typical trough container system (right) (2013)

In both modular panel and trough container systems, plants are usually pre-grown and established before installation. They both require regular irrigation and feeding and since vegetation units are arranged vertically, each raw of panel or trough is usually irrigated individually from the top to distribute water evenly throughout the vertical units. The excess water is drained to the back of the units, and thus excess nutrients and contaminants will not travel down to the lower units and saturating them.

Living wall systems add a considerable load to a walls structure when they are directly mounted on a buildings surface. Fully planted and saturated units weigh between 40-70kg/m^2 and the larger the substrate mass, the heavier the vegetation becomes such as the case of trough system (ANS Group 2010; Biotecture Ltd 2014; Treebox Ltd 2013).

Felt base system

Felt base living walls use more design oriented techniques to create visually striking vegetation cover as planting options are more flexible. The method uses layers of propagation felt fixed onto the building wall over a waterproof membrane and the plants are inserted into slits cut into the top layer of felt. The roots of plants grow in ‘pockets’ created between two sheets of felt. This allows for the creation of random patterns on the wall canvas and a flexible mixture of plant species to grow within the system. The pioneer of this type of wall vegetation is the French botanist Patrick Blanc. His methods include the mimicking of the hydroponics mechanism of plants growing on vertical cliffs in humid climates. This type of living wall requires vast amounts of water as the growing medium, in this case layers of felt, is not designed to retain water and needs to be constantly irrigated and fed in order for plants to survive (Dunnett and Kingsbury 2008).

Figure 2.13 Patric Blanc’s felt based living wall installed at the Athenaeum hotel in Piccadilly, London. 280 varieties of plants are used to withstand the elements on the exposed eight story wall and create a three-dimensional vertical garden (2011)

Other types of living wall systems are currently being developed and tested by green wall manufacturers and landscape designers to accommodate different climatic conditions and the different purposes of wall greening. Some prototype systems are designed to use little or no irrigation as the existing systems require regular irrigation and maintenance to accompany them, which can potentially reduce or even offset the environmental benefits they can provide (Natarajan et al. 2015; Perini and Rosasco 2013).

Figure 2.14 'Moss wall' exhibited at Ecobuild London, green moss is grown on the panels made of compressed recycled plastic (left, 2011), and a green wall exhibited at the Chelsea Flower Show designed to require little irrigation by using moss and succulents growing inside terracotta tubes (right, 2013)

New system developments and diverse methods currently available for wall greening mean classification of green walls is not yet standardised as is so in the green roof industry. This thesis focuses on relatively well established and commercially available methods of green wall installation including the 'green screen' system incorporating climbing plants and supporting panels as well as two types of living walls using modular panels and a trough container system.

2.4. Conclusion

This chapter explained the classifications of green roofs and walls used in this thesis and the characteristics of various systems currently used within the industry.

Green roofs are generally categorised by the thickness of the substrate layer as this determines the variation of plant species a roof can accommodate, which in turn defines the usage of a green roof. ‘Intensive green roofs’ consist of a substrate of over 200mm that can support a diverse variety of plants and are often used as roof gardens whereas ‘extensive green roofs’ have less than 100mm substrate layer and are often installed for other purposes than recreational spaces. A roof consisting of a substrate thickness between those two is called a ‘semi-intensive green roof’.

Classifications of green walls are usually based on the configuration of a vegetation system. Green walls can be divided into two major categories such as ‘green façades’ and ‘living walls’. They are fundamentally different in terms of arrangement of the substrate within a vegetation system. Green façades provide a cover of only climbing plants with a mass of growing medium encased within a container at the bottom of the foliage. The growing medium of living walls forms a continuous layer behind the foliage similar to green roofs and providing a uniform substrate cover over a wall.

Where the thermal benefits of green envelopes are concerned, this configurational difference in green walls as well as the varying depth of green roof substrate layer can be a significant influential factor in determining the performance of a vegetation system. Therefore, this thesis focused on investigating how system varieties can influence the thermal performance of green roofs and walls, and experiments were carried out on green roofs of different substrate thicknesses (Chapter 4) and also a green façade and three types of living wall systems including modular panels (compost-based and hydroponic) and trough container (Chapter 5).

3. The thermal impacts of green roofs and walls on buildings

In Chapter 3, existing studies and knowledge with regards to the thermal impacts of green roofs and walls on buildings are explained in order to support research concepts for this thesis. Section 3.1 explains how the thermal performance of a building's envelope can influence energy consumption. Also explained is the potential use of green roofs and walls for passive cooling and as an insulation material. Research methodologies used in existing studies and the most relevant outcomes to this thesis are introduced in Section 3.2. Section 3.3 summarises key previous findings and also describes how they became the basis for the development of this study.

3.1. Potential for green roofs and walls as building insulation materials

3.1.1. Urban built environment and energy demand

The Majority of the world's population now lives in urban areas, and in the UK, the current proportion of urban residents exceeds 80% of its population. (Royal Comission on Environmental Pollution., 2007). Our transition from rural to urban living has made a significant impact on our environment, as natural landscapes are transformed into cityscapes with hard and high surfaces to support economic growth and accommodate vast numbers of inhabitants. As Gilbert (1991) stated, the modification of surface accompanied with the loss of green mass have created unique micro climates within built-up urban areas, characterised by significantly higher air temperatures, higher humidity due to a lack of airflow and higher amounts of pollutants in the atmosphere compared with surrounding semi-rural and rural areas.

This phenomenon is called the Urban Heat Island (UHI) effect and this 'urban warming' has a significant impact on both the total energy consumption and peak demand for electricity in the building sector due to the increased energy required to achieve thermal comfort for building occupants (Santamouris et al., 2001). It also affects the economy in cities as McPherson (1994) projected that the UHI effect would be responsible for 3–8% of the total electricity demand in the United States. Several studies have been carried out to investigate parameters that can influence electricity demand including climatic conditions, economic, social and demographic factors. Many studies have concluded that the ambient temperature has the single most significant impact. An increase in the use of air conditioning encouraged by temperature increases and also improved general living standards have resulted in a higher correlation between energy demand and ambient temperatures in cities (Perez-Lombard et al., 2008, Sailor, 2001).

Table 3.1 Impacts of ambient temperature increases on total electricity consumption found in separate studies (Source: Santamouris et al., 2015)

City / Country	Reference year	Increase in total electricity load / ℃ (temperature rise)
Singapore	2003–2012	1-2.5%
Hong Kong	2003	4.0%
Bangkok, Thailand	1986–2006	7.49%
New Orleans USA	1995	3.0%
California, USA	2004–2005	7.7%
Louisiana, USA	1984–1993	8.5%
Netherlands	1970–2007	0.5%
Spain	1998	1.6%
Athens, Greece	1993–2001	4.1%

Santamouris et al. (2015) analysed existing studies that had investigated the effects of rising ambient temperatures on energy demands in different regions of the world concluding that each degree of temperature rise could result in an increase of peak electricity demand of between 0.5–4.6% and a total consumption of electricity between 0.5–8.5% (See Table 3.1.) The impact on the total electricity consumption due to temperature increase was more significant in cities with warmer climates such as Bangkok, Louisiana, and Athens. In those cities, additional peak electricity demand for cooling is increasingly becoming an issue as it puts pressure on existing power plants and construction of additional facilities becomes necessary to meet increased energy demand.

As well as geographical aspects and weather conditions, thermal performance of buildings and what occupants perceive as a 'comfortable temperature' inside also had a significant impact on the electricity demand (Sadineni et al., 2011). Those results demonstrated the importance of designing buildings and urban structures to adapt to climatic conditions in order to reduce the effects of increasing ambient temperatures due to global warming and the Urban Heat Island effects on electricity consumption.

3.1.2. Impact of building envelope on energy consumption

In developed countries, buildings contribute to over a third of the total energy consumption. In 2004, buildings consumed 37% of the total energy in the EU, exceeding the figures for both industry and transport combined which were 28% and 32% respectively. Building energy consumption is steadily rising, at a rate of 0.5% in the UK, 1.5% in the EU and 1.9% in North America (Perez-Lombard et al., 2008). Such increases are due to growing populations and economies, improved building services and the extended time people spend inside buildings. The largest contributory factor has been the increased use of heating, ventilation and air conditioning (HVAC) systems to meet the high level of indoor comfort that occupants demand today. HVAC systems are now the largest element of energy consumption both in domestic and non-domestic buildings. Table 3.2 shows that in Europe, over 60% of the energy in residential buildings is consumed to achieve the required thermal comfort of occupants, a significantly higher ratio compared to other end uses. In fact, energy used by HVAC systems accounts for around 50% of the total energy consumption in buildings and 20% of the total energy consumption in developed countries (Pacheco et al., 2012).

Table 3.2 Energy consumption by end uses in residential buildings in 2003 (Source: Perez-Lombard et al., 2008)

Energy use (%)	USA	EU	UK
Space conditioning	53%	68%	62%
Domestic hot water	17%	14%	22%
Lighting and appliances	30%	18%	16%

This has prompted countries and researchers around the world to look at requirements and potential improvements to be made on energy efficiency in buildings, and to date, 82 nations have signed up to the World Green Building Council (WGBC) with initiatives to improve the sustainability of buildings. Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Methodology (BREEAM), are two of the leading environmental assessment and certification systems for construction in the world, both identify energy efficiency as an essential element of sustainable building (Sadineni et al., 2011).

Energy efficient buildings should be required to implement a minimum energy standard in order to achieve desired environmental conditions. Two major factors that influence the energy consumption of a building are the buildings envelope including roof, walls and windows and also heating and cooling systems for controlling indoor thermal comfort (Manioˇglu and Yilmaz, 2006).

A building envelope separates the internal and external environments of buildings. Since the indoor thermal conditions of a building are defined by the envelope, it determines the energy required for regulating indoor air temperature for the occupants. Thus, designing the components of the building envelope according to certain climatic conditions can have a positive impact on the total energy demand of a building. There are a number of design elements which will influence indoor thermal comfort and consequently the energy consumption of a building including orientation, shape, and also the thermo-physical properties of the envelope (Sadineni et al., 2011).

In recent years, standards required for building envelopes in new development projects have become increasingly higher, and as a result, thermal performance of construction components has largely improved. Various code standards require a certain U-value to be met in elements of a new build including wall, floor and roof. A U-value represents a heat transfer co-efficient of a building component and the lower the value the better the thermal performance achieved (Pacheco et al., 2012). Today, almost all external building components need to comply with this maximum U-value for thermal standards in the UK (John et al., 2005). Table 3.3 shows the improvements made in U-values required in building elements over a period of time in the UK, indicating how the importance of energy conservation in building has grown and how much impact such action on the external elements can have on the overall energy consumption of a building.

Among these elements, walls make up a large portion of a building's envelope and act as a thermal and acoustic barrier between outdoor and indoor environments. The thermal performance of a wall heavily influences the heat entering and escaping through the structure and also the amount of energy required for controlling thermal comfort inside. Thermal resistance of walls becomes especially important in buildings with a large proportion of vertical surfaces such as high-rise buildings (Sadineni et al., 2011).

Along with walls, roofs are also an essential part of the building envelope. The roof of a building is particularly exposed to solar radiation and accounts for a large portion of the total heat gained and lost. Currently in the UK, the upper limit of U-value for roofs of new builds is set at 0.25W/m^{2}K whilst the value for walls is 0.30W/m^{2}K (Department for Communities and Local Government, 2015). This emphasises on thermal resistance of roofs is perceived as being essential in improving the overall thermal performance of buildings and reducing energy demand for heating and air-conditioning.

Table 3.3 Changes in the minimum standard U-values (W/m2K) for UK buildings over time (Source: John et al., 2005)

<table>
<tr><th>Element</th><th>1976</th><th>1985</th><th>1990</th><th>1995</th><th>2002**</th></tr>
<tr><td>Walls</td><td>1.0</td><td>0.6</td><td>0.45</td><td>0.45</td><td>0.35</td></tr>
<tr><td>Pitched roof</td><td rowspan="2">0.6</td><td rowspan="2">0.35</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td>0.25</td></tr>
<tr><td>Flat roofs</td><td>0.16*</td></tr>
<tr><td>Floors</td><td>1.0</td><td>0.6</td><td>0.45</td><td>0.45</td><td>0.25</td></tr>
</table>

* The value was changed back to 0.25 in 2006

** Since 2006, u-value limits still apply but are no longer sufficient by themselves to meet the regulations and the calculation of either Dwelling Emission rate (DER) or Target Emission rate (TER) is also required

3.1.3. Vegetated envelope for passive cooling and insulation material

There are several ways to improve energy efficiency in buildings, and while improvements to mechanical heating, cooling and ventilation systems are categorised as active methods, improving the elements of the building envelope is considered a passive strategy (Pacheco et al., 2012). This passive approach has increasingly been seen as a viable option to address the issues of environmental costs of building operation, with vegetated roofs and walls often considered a passive measure to improve the thermal performance of the building envelope (Peck et al., 1999).

The external surface of building envelopes including roofs and walls are consistently subjected to extreme temperature fluctuations due to the changes in outdoor air temperature and also exposure to solar radiation and wind. In warm and sunny periods of the year, a vegetation layer on a roof or wall can provide a cooling effect by shading, absorbing solar radiation and converting it into latent heat by evapotranspiration. This means less radiated heat reaching the buildings surface by reflecting it back into the ambient air (Suzuki, 2008, Takakura et al., 2000). Evapotranspiration is the sum of water transferred to the atmosphere from a plants surface by transpiration and from the soil’s surface by evaporation. Plants consume solar energy absorbed into leaves in the process of pumping water from the roots and releasing moisture as vapour. This prevents the energy within solar radiation being released as heat into the air (Hien et al., 2007, Perini et al., 2013).

Minke and Witter (1982, cited in Ottelé, 2011) stated that only 5-30 % of the total solar energy plants receive is transmitted through the vegetation layer as the majority (10-50%) is reflected back or released back into the air as radiant heat and up to 40% is consumed by the plants for photosynthesis and evapotranspiration. This demonstrates how effective vegetated envelopes are in significantly reducing heat reaching a building's surface and consequently, entering the building through the envelope.

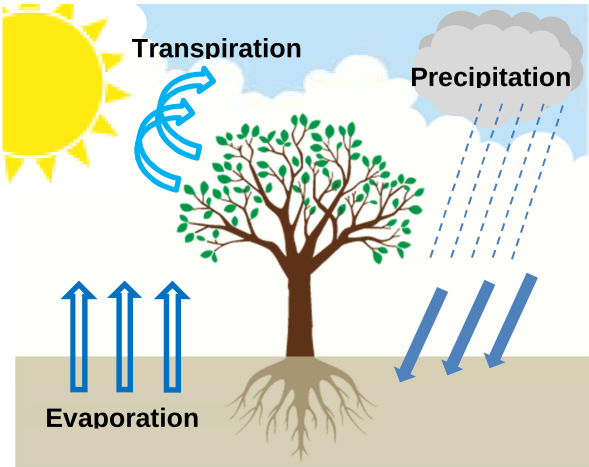


Figure 3.1 Mechanism for evapotranspiration by a vegetated surface

Systems of green roofs and walls usually consist of plants and a layer of growing medium such as organic compost. As previously mentioned, such components provide shade and absorb radiation in summer; they can also create a wind and thermal barrier over a buildings surface in colder periods of the year. Air trapped inside the foliage of plants and in the space between the vegetation layer and building surface as well as the thermal mass of the growing medium layer could provide thermal resistance and insulation (Bass, 2007, Teemusk and Mander, 2010).

The effectiveness of green roofs and walls as passive cooling and building insulation material are often demonstrated by way of reduced building surface temperatures in warmer climates and in some cases, increases in temperatures in cold climates. The surface temperature of an envelope will directly influence heat gains and losses through a building's exterior when roofs and walls are subjected to extreme temperature differences between the interior and exterior of a building.

3.2. The impacts of vegetated envelopes on the thermal performance of buildings

This section explains the findings of previous studies on the thermal effects of green roofs and walls that are most relevant to this thesis. A summary of methodology used in those studies is described first including merits and limitations, followed by the findings regarding impacts of green roofs and walls on the thermal performance of a building's envelope.

In the past fifteen years, along with a rising popularity to use vegetation incorporated into building design, there has been an increasing number of studies conducted to investigate the thermal impacts of green roofs and walls. Those existing studies can be broadly divided into three categories depends on approaches: 1) field experimentation, 2) laboratory experimentation and 3) numerical and simulation studies. Some studies have combined a theoretical approach with experimentation to either acquire the necessary data to construct a numerical model or validate simulation results.

1) Field experimentations

Taking thermal measurements of buildings with vegetation cover has been the most simple and common method to investigate the thermal performance of green roofs or walls. Although the results can be case specific, these studies are useful for the evaluation of individual vegetation systems and also the assessment of performance in specific conditions such as system configuration and climate. This is because the thermal characteristics of vegetation vary and are influenced by numerous factors including plant type and coverage ratio, substrate material, thickness, moisture content and weather (Wong et al., 2003a, Arima et al., 2005, Fang, 2008, Jim and Peng, 2012). A number of studies have been conducted on green roofs and walls installed on actual buildings and in some cases using test cabins. Temperature measurements were often taken on internal and external surfaces of the envelope, also indoor air when there were two or more comparable internal spaces. Heat flow through the structure was also the focus of many studies; data was acquired either employing a numerical approach using collected temperature data or by physical measurements from heat flux sensors.

2) Laboratory experiments

In contrast to field experimentations, there have been limited controlled studies on the thermal characteristics of green roofs and walls. Laboratory experiments allow researchers to acquire accurate data sets by reducing transient elements and controlling environmental parameters including temperature, relative humidity and solar radiation using a wind tunnel or environmental test chamber. Previous studies have used this approach to explore the influence of certain elements on the overall performance of vegetation systems such as the evaporative cooling rate of vegetation (Onmura et al., 2001), plant species and foliage coverage, (Fang, 2008) substrate compositions and moisture level (Sailor et al., 2008).

3) Numerical models and computer simulations:

Building a thermal model of vegetation poses its own challenges due to the complex heat and mass transfer mechanisms influenced by shading, evapotranspiration and the thermal mass of organic components (Liu and Baskaran, 2003). At first, researchers used simple approaches to build thermal models of vegetation by using steady-state R-values or modifying radiative properties of the envelope to account for foliage cover. As the understanding of thermal transport phenomena in green roofs gradually improved, more comprehensive models were developed by applying heat and mass balance across the vegetation layer and calculating its evapotranspiration (Tabares-Velasco, 2009). Sailor (2008) developed an energy balance model for green roofs which has been integrated into the building energy simulation software DesignBuilder and EnergyPlus. Other researchers have developed a heat and mass transfer model of green roofs and walls within another transit simulation program TRNSYS, some by acquiring hydrothermal behaviour data and others validating the simulation results against physically measured temperature data (Ouldboukhitine et al., 2014, Sfakianaki et al., 2009, Djedjig et al., 2015). These thermal models were later applied in simulation studies to assess the impacts of vegetation on the energy performance of a particular building (Feng and Hewage, 2014, Gupta et al., 2011) or compare the performance in various climates (Djedjig et al., 2015).

3.2.1. Regulation of external surface temperatures for roofs and walls

Various studies have investigated the impacts of vegetation on external surface temperatures of a building's envelope as it signifies the ability of green roofs and walls to decrease heat flow through the structure. External temperature measurements are also useful for validation of theoretical models (Tabares-Velasco, 2009) and an important parameter in studies focusing on the mitigation of the UHI effects (Ng et al., 2012, Susorova et al., 2014). In studies on life-cycle costs of green roofs and walls, the effects of vegetation to regulate surface temperatures and reduce thermal stress on a building's external structure are also considered as economic benefits in way of extending the life of wall construction materials (Ottelé et al., 2011, Perini and Rosasco, 2013).

Previous studies have shown that green cover reduces the daily fluctuation of external surface temperatures on roofs and walls. An exposed hard surface of a building is subjected to radiation heat gain from sunlight during the day and radiant losses due to the exposure to cooler ambient air at night, causing the daily surface temperature to fluctuate significantly. Vegetation cover reduces this diurnal fluctuation by reflecting sun rays, providing shading and evaporative cooling during the day, and insulating the surface at night (Liu and Baskaran, 2003, Arima et al., 2005).

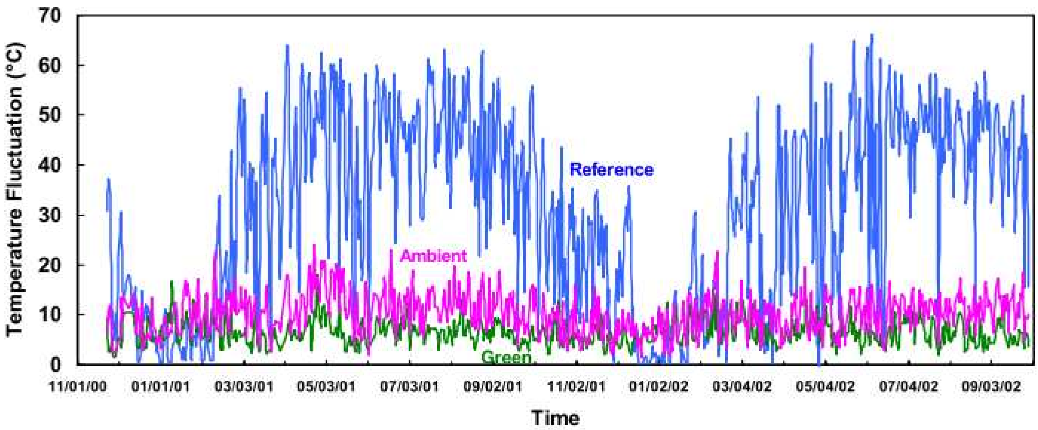


Figure 3.2 Surface temperature of roof membrane recorded in Ottawa, Canada, showing the green roof significantly reduced the daily temperature fluctuations compared to a reference roof throughout the two-year observation period (Source: Liu and Baskaran, 2003)

Figure 3.2 shows the results of a two-year field experiment conducted by Liu and Baskaran (2003) in Ottawa, Canada, demonstrating that green roof cover significantly reduced the daily temperature fluctuations on the roof membrane, particularly in spring and summer. The average diurnal temperature fluctuation of the exposed roof membrane over the study period was around 45℃ while the green roof reduced this to around 6℃. Liang and Huang (2011) and Sano et al. (2001) also reported that the green roof substantially reduced the daily variation of roof surface temperatures from 25–35.4℃ to 2–3.5℃ in summer.

Summer

A number of existing papers state that vegetation decreases the daily peak surface temperature of a conventional building envelope such as bituminous, concrete and brick. Field studies conducted in various climates observed the conventional roof surface reaching extremely high temperatures during the day, reporting a diurnal maximum temperature of 54–70℃ recorded around 1pm when solar radiation was at its daily peak. On the contrary, vegetation stabilised the surface temperature by reducing the radiant heat reaching the roof, lowering the peak surface temperature by 22–35℃ (Sano et al., 2001, Liu and Baskaran, 2003, Sonne, 2006, Simmons et al., 2008, Liang and Huang, 2011).

The variation in maximum temperature reduction on the building's external surface due to green walls was larger than the green roofs, between 5.7–25.1℃ despite that all reviewed studies were conducted during summer months in similarly warm climate (humid subtropical climate in Asia or Mediterranean climate). Contributory factors to this variation were system type and the orientation of the wall. Green façade with climbing plants showed less temperature reduction effects at 5.7–8.9℃ with the least impact on an east-facing wall (Nojima and Suzuki, 2004, Eumorfopoulo and Kontoleon, 2009, Hayano et al., 1985). Living walls consisting of a substrate layer decreased the daily maximum surface temperature by 11.5–16℃ (Wong et al., 2010, Cheng et al., 2010, Chen et al., 2013). An exceptional temperature reduction of 25.1℃ and also the highest peak temperature of 63℃ were observed by Olivieri et al. (2010) near Madrid, Spain, where the total annual global horizontal irradiation is double the UK average and the highest amongst regions where studies were conducted. Their living wall system also consisted of a 70mm polystyrene insulation layer (0.035 W/mK), and thus, the impact may not have been exclusively provided by the vegetation. All the tested living walls were facing south or southwest and none of the green wall studies looked at north-facing vegetation as their focus was on reduction of solar radiation gain and surface temperatures in summer.

Green covers were also found to delay radiation heat reaching the building's external surface. Simmons et al. (2008) reported that all six types of green roofs they tested delayed the temperature peak on the roof membrane by 1–3 hours, and Spolek (2008) observed the same delay of 4–6 hours.

Many studies also found vegetation had an undesirable insulating effect during the night preventing radiation heat released through the building's surface in warm seasons. Sano et al. (2001) observed the vegetation cover increased the roof surface temperature by approximately 2℃ during the night on a summer day in Yokohama, Japan, and Sonne (2006) recorded an average increase of 7℃ across the two-month field experiment in summer in Orlando, Florida, USA.

Some green wall studies also found this increase in daily minimum temperatures although the difference between the exposed and vegetation-covered walls was smaller than the green roof at 0.5℃ (Nojima and Suzuki, 2004, Olivieri et al., 2014)

Winter

The insulating effect of green roofs and walls is mostly due to thermal resistance of the substrate layer and in some cases, the unventilated air gap created between the vegetation and the building's surface, which functions favourably during the cold period of the year (Yamada et al., 2004, Liu and Baskaran, 2003).

As most existing experiments focus on temperature reduction in summer within a tropical and subtropical climate, available external temperature data in cold periods of the year is still limited. Simmons et al. (2008) found roof membrane temperatures under the green roof test beds stayed 2–5℃ warmer than conventional roofs on days when the minimum outdoor temperature was around 5℃ in Austin, Texas, USA. L iu and Baskaran (2003) also stated that the green roof increased the daily minimum roof membrane temperatures in early winter in Ottawa, Canada, although the amount of increase was not specified. Their study also found this effect was dissipated when heavy snow accumulated on the tested roofs in January. This result was repeated by Teemusk and Mander (2007) in Tartu, Estonia, where an over 200mm thick layer of snow cover provided greater insulation to the roofs and made the impact of the green roof unnoticeable.

The effects of vegetation in decreasing daytime peak surface temperatures were also apparent in cold seasons as Sonne (2006) observed. A 180mm green roof reduced the daily maximum temperature of the roof membrane from 36℃ to 18.6℃. Although this was recorded in the humid subtropical climate in Orlando, Florida, USA, it indicates a potential adverse effect of green roofs and walls in reducing the external surface temperatures in colder climates such as the UK.

3.2.2. Impacts on indoor thermal conditions

The effects of vegetation cover on the external surface temperature of an envelope can be transferred into the internal space of a building. Many previous studies found that green roofs and walls reduced the inner surface temperatures of the structure as well as indoor air temperature in summer and increased them in winter.

Summer

Four similar field experiments carried out in Japan found that green roofs decreased both the internal roof (ceiling) surface and indoor air temperatures. In those studies, researchers recorded temperature measurements inside two identically shaped and orientated rooms with vegetation covering the roof of one of the observed rooms. Higashijima et al. (2001) stated that the ceiling surface temperature of the room with an exposed roof fluctuated between 31–35℃ peaking at around 6pm whilst the ceiling temperature of the room with a green roof stayed constant at around 30–31℃ throughout the day. The continuous t emperature rise of the inner surface of the exposed roof during the late afternoon indicated that radiation heat was stored within the structure during the day and gradually released into the indoor air.

The Japanese studies observed that green roofs reduced the average daily temperature of the ceiling surface by 1.5–4.5℃, and all four reported that roof vegetation decreased the daily indoor air temperature by 1℃ as demonstrated in Figure 3.3 (Sano et al., 2001, Okamoto and Sunaga, 2006, Ochiai et al., 2006, Saki et al., 2006).

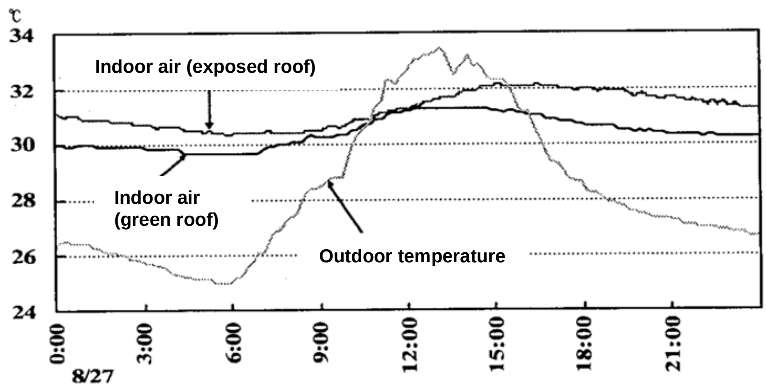


Figure 3.3 Recorded indoor air temperature of two tested rooms on a summer day in Yokohama, Japan (Source: Higashijima et al., 2001)

Green wall studies also reported similar ranges of internal temperature reductions owing to vegetation. Eumorfopoulo and Kontoleon (2009) observed climber cover on an east-facing wall reduced both mean internal surface and indoor air temperatures by 0.9℃ over a summer month in Thessaloniki, Greece. Cheng et al. (2010) also reported a constant surface temperature reduction of over 2℃ in a room with living walls installed on the southwest facing wall. In their study conducted in Hong Kong, the internal space consisted of two test rooms which were air-conditioned at the same temperature. They also identified a delayed peak temperature as mentioned in green roof studies, stating that the surface temperature continued to increase in the evening and peaked around 22:00.

Simmons et al. (2008) observed more substantial internal temperature reductions in experiments using metal test cabins in Austin, USA. On a day when the outdoor air temperature reached 33℃, the air temperature inside the metal cabins reached as high as 54℃ under the black membrane roofs whilst the internal temperature of the green roof cabins ranged between 36–38℃. A field study on green façades using a portable cabin consisting of 47mm uninsulated cement wall also showed a larger reduction in internal air temperature (from 30.3℃ to 24.7℃) compared to other green wall studies (Nojima and Suzuki, 2004). The large reduction of internal temperatures in these studies can be explained by the low thermal resistance of the tested roofs and walls along with a high ratio of roof or wall surface area against the total building surface.

Winter

Okamoto and Sunaga (2006) observed two thermally identical rooms, one with a green roof and the other without over the month of January when the average maximum temperature was 10℃ and the minimum temperature was 0℃ in Tokyo. The results of measurements taken at weekends when the classrooms were not occupied or heated showed that on average, the ceiling surface temperature under the green roof was 1.5℃ higher and the indoor air temperature was 2℃ higher than the room without green cover during the observation period. A similar study carried out by Takakura et al. (2000), also in Japan, showed slightly less of an impact and the increase in daily average temperatures of both ceiling surface and indoor air due to a green roof were within 1℃. This was echoed by Simmons et al. (2008) who stated there was no significant difference in internal temperatures among the eight test cabins for conventional roofs and green roofs on a cold day when the minimum temperature was around 5℃ in Austin, USA.

3.2.3. Heat flow and energy load reductions

A number of studies looked at the effects of green roofs and walls in reducing heat transferred through a building's envelope. When there is a temperature difference between external and internal surfaces of a building, thermal energy will be transferred from warmer to cooler surfaces (Nojima and Suzuki, 2004). By moderating the influence of outdoor variables on a building's exterior surface, vegetation cover can decrease the temperature difference between the outer and inner surfaces of an envelope. This consequently reduces heat transferred through the external structure of buildings.

Heat flow through the structure

For assessment of the effects on heat flow, certain existing studies used heat flux sensors to measure the actual heat exchange occurring on a building's surfaces. These measurements were taken either externally or internally (Liang and Huang, 2011, Fioretti et al., 2010, Iwayama and Tarumi, 2006). Other studies took a numerical approach to determine the reduction of heat gained and lost through the envelope using temperature measurements collected in field experiments (Jim and Peng, 2012, Wong et al., 2003a, Sonne, 2006, Spolek, 2008, Eumorfopoulo and Kontoleon, 2009).

Liang and Huang (2011) recorded measurements of heat flux on the ceiling surface under a 130mm turf green roof and reported that on a typical summer day in Taiwan, heat gain was observed almost all day under the exposed concrete roof whilst constant heat loss was recorded under the green roof, resulting in a daily average heat flux of -0.25 W/m² for the green roof and 19.21 W/m² for the reference roof.

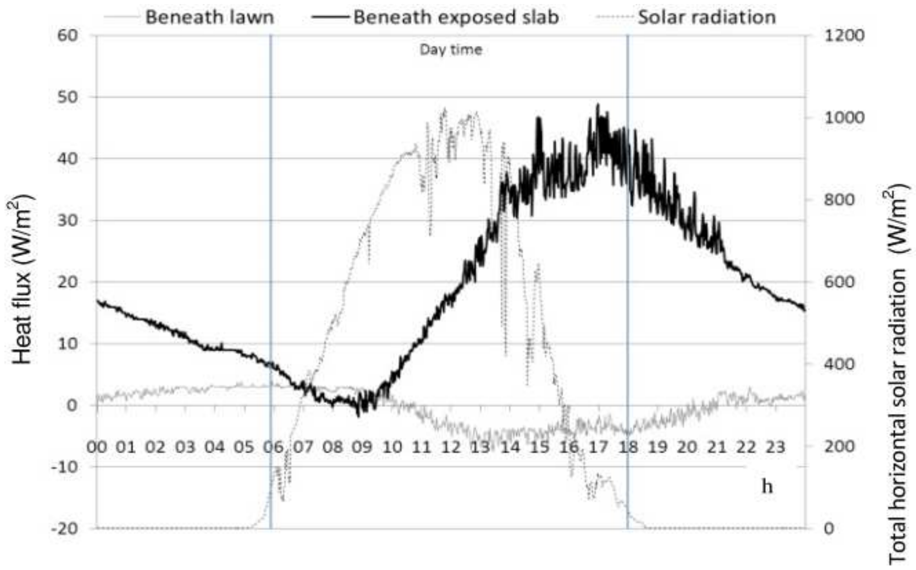


Figure 3.4 Diurnal heat flow measured at the inner roof slab surface on a summer day, showing the effects of a turf roof in minimising heat gained through the roof structure (Source: Liang and Huang, 2011)

In the same humid subtropical climate, Cheng et al. (2010) measured heat flow on the internal surface of a 300mm uninsulated concrete wall facing west while the internal space was air-conditioned. Recorded peak heat flow through the wall without green cover was 40W/m^2, a similar figure to the exposed roof's graph in the figure above. Hydroponic living wall panels significantly reduced the incoming radiant heat and accordingly heat flux through the vegetated wall did not exceed 10W/m^2 throughout the 40-day experiment in Hong Kong.

A significant moderation of heat flow during the summer months was also observed by Liu and Baskaran (2003) in the humid continental climate of Ottawa, Canada. Results of heat flux measurements on the roof surface showed that the roof membrane which was exposed to the elements experienced heat gain in the afternoon and heat loss during the night, while the green roof substantially decreased the amount of total heat flow throughout a day. They found that green roof was more significant in reducing heat gain in spring and summer than heat loss in the cold period of the year. Over the 22-month observation period, the green roof reduced daily heat gain by 95% and heat loss by 26%. They concluded that the heat flux reduction would be more significant in warmer regions as the energy demand in Ottawa is predominantly for heating.

In numerical studies using temperature measurements collected in field experiments, heat flow per unit area Q [W/m2] was calculated based on the temperature difference between the external surface (T_{se}) and internal surface (T_{si}) of a roof or wall structure:

$$Q = K\frac{(Tse - Tsi)}{\Delta t} \qquad (3.1)$$

where K is the thermal conductivity and Δt is the thickness of the roof or wall material without vegetation components (Jim and Peng, 2012).

Jim and Peng (2012) found that green roof eliminated heat gain occurring through the roof structure on sunny and cloudy days over a summer month in Hong Kong and also increased by approximately threefold the amount of heat loss when compared to the exposed reference roof. Significant heat flow reductions due to vegetation cover in a subtropical climate were also reported by Wong et al. (2003a) and Sonne (2006) on green roofs and by Eumorfopoulo and Kontoleon (2009) on green walls.

In the temperate climate of Portland, USA, Spolek (2008) found that the reduction of heat flow due to green roof in summer was considerably higher than in winter based on heat flux calculations using temperature data collected during a three-year observation. The green roof reduced average hourly heat flow through the roof structure by 72% in mild and dry summers whilst the reduction in winter was significantly lower at 13%.

Energy loads of roof and wall

The effects of green roofs and walls in reducing energy consumption for mechanical heating and cooling often becomes an issue of debate as it is one of the most quantifiable economic benefits of vegetation. In existing studies, the energy loads of a building have been assessed by either calculating the amount of ‘unfavourable heat flow’ through the structure or monitoring the actual electricity consumption for heating and air-conditioning using test rooms.

Kamitomai and Tarumi (2007) analysed the reduction of energy loads due to a green roof using heat flow measurements recorded in a field experiment in Kanazawa, Japan. In this study, the reduction of unfavourable heat flow—heat gain in air-conditioning seasons and loss in heating seasons—was considered to be the reduction of thermal loads for mechanical heating and cooling. They found that green roof with 240mm substrate layer reduced the annual daytime (9:00-17:00) energy loads due to heat flow through the roof by 43%. As many of the heat flow studies in the previous section reported, this was primarily due to the substantial reduction of heat gain in summer rather than heat loss in winter.

Jim and Peng (2012) calculated the potential daily energy load reduction for air-conditioning by assuming the accumulated heat gain through the roof over a 24-hour period to be daily cooling loads, and concluded the green roof reduced energy loads by 0.9 kWh/m^2 on sunny summer days in Hong Kong (reduction ratio against the reference roof is not specified).

Ochiai et al. (2006) assessed the reduction of cooling loads on a green roof by monitoring actual electricity consumption for air-conditioning in two identical unoccupied classrooms in Yokohama, Japan. During the 20-day observation period in summer, the green roof was installed to cover the roof of one of the observed rooms while both were air-conditioned to be kept at the same temperature. They concluded that a green roof reduced the daily cooling load by 23% in summer based on the reduction of electricity consumption over 24 hours. However, those figures may not represent the potential energy load reductions as many buildings are not occupied or air-conditioned for 24 hours a day.

In Hong Kong, Cheng et al. (2010) carried out a similar experiment testing hydroponic living wall panels installed to cover the west-facing wall of a monitored room. The room was air-conditioned to keep the indoor temperature at 26℃, and electricity consumption fo r the room and an identical room directly above without green cover were recorded over forty days in autumn. They reported the living walls reduced the average daily energy consumption for cooling by 1.45 kWh in a room of 9.2m^3 (actual consumptions were not specified).

All of the above studies were carried out in subtropical climates in East Asia, mostly focusing on the reduction of air-conditioning load. A simulation study conducted by Djedjig et al. (2015) using a transit simulation program (TRNSYS) that compared a green wall’s performance in the Mediterranean and maritime temperate climates found that the impacts of vegetation systems were more significant in a hot climate. The green walls reduced 50% of cooling load in both examined climates; they also reduced heating load by 11.9% in the temperate climate and 8.7% in the Mediterranean. Substantial cooling load reductions due to green walls coupled with five times higher initial cooling loads meant the total energy savings were much greater in the warmer climate.

Also on the subject of green walls, the impacts of vegetation on energy loads may vary depending on the orientation of the wall which determines the amount of solar radiation exposure on its exterior surface. A theoretical study employing a thermal-network model conducted by Kontoleon and Eumorfopoulou (2010) found that the effects of green walls were more prominent on east and west facing walls, and the reduction rate of a building air-conditioning loads for such walls was more than double the figure for south and north facing walls in the Mediterranean climate of Athens. Another simulation study also demonstrated the maximum reduction of the cooling load was found on the west facades in the temperate climate of northwest France (Djedjig et al., 2015).

3.2.4. Factors that influence the thermal performance of green roofs and walls

Previous studies have also looked at more than one type of green roof or wall system in various configurations in order to investigate how certain factors would influence the thermal performance of vegetation including type of plants, substrate material and thickness. Findings generally suggest that components and design of vegetation systems as well as the construction of the original building envelope greatly affect the level of thermal benefits green roofs or walls can achieve.

System compositions

Simmons et al. (2008) tested six commercially available green roof systems using test cabins in Austin, Texas, USA, and found that there was little variation in roof surface temperatures among the tested systems. They concluded this was due to the basic composition of the green roof designs being very similar, all consisting of 100mm substrate with only a slight variation to the materials and vertical arrangement.

Yamada et al. (2004) looked at the influence of substrate thickness on the heat flow through the roof slab by comparing two turf roofs consisting of 75mm and 150mm soil layer in Wakayama, Japan. The results revealed that on a summer day, the shallower green roof showed better performance in reducing the lower roof slab surface temperatures as well as the total heat flow through the roof. They stated that as substrate for both roofs had a similar evaporation rate, the difference in their ability to reduce radiation gain was marginal during the day; however at night, the thinner substrate with less thermal resistance helped to release radiant heat, resulting in larger heat loss through the roof under the 75mm vegetation compared to the 150mm.

Another study conducted in Kanazawa, Japan by Iwayama and Tarumi (2006) showed a contrasting result to this, and the seven-month monitoring on 80, 160 and 240mm green roofs revealed the thicker substrate showed better performance in reducing both heat gain through the roof in summer and heat loss in winter. Reduction rates for these heat flows against the uninsulated reference roof were 60% for the 240mm green roof, 53% for the 160mm and 42% for the 80mm. Interestingly, the main material of the substrate used in this study was perlite which is an industrial mineral product consisting of lightweight globules often used as plant growing medium and also as loose fill insulation material for its low thermal conductivity. Thus, it is possible that the results were influenced by the high thermal resistance of this particular substrate component being that its performance simply improved as its mass (thickness) increased.

Yamada et al. (2004) also compared the performance of green roofs in two different depths with a 40mm polyethylene insulation panel underneath. In winter, adding an insulation layer increased the performance of green roofs in reducing heat loss through the roof, and the inner slab surface under the 75mm green roof became approximately 5℃ cooler than the green roof with added insulation when the internal space was mechanically heated. However, they also stated this effect would not always be positive as it would also decrease the night-time heat loss through the roof in summer.

Wong et al. (2010) installed test beds consisting of seven different living walls and a climber panel on a free-standing wall comparing the impacts of each vegetation system on the wall surface temperature and ambient air temperature in Singapore. Recorded surface temperatures varied with a maximum of 5℃ amongst the systems which suggested the climber panel without a substrate layer was less effective in reducing temperature behind the vegetation. However, the only green façade system tested in the study did not have sufficient foliage cover during the observation period to provide viable measurements and required further examination as Safikhani et al. (2014) recommended in their review.

Plants and foliage mass

Few existing papers demonstrated the apparent correlation of the thermal performance of green roofs and walls against plant coverage ratio and the amount of foliage mass.

Results of a simulation study conducted by Takakura et al. (2000) showed that the temperature reduction on the roof surface was highly related to the leaf area index (LAI) which represents the amount of leaf material in a canopy, this was later validated by field measurements. Wong et al.

(2003a) carried out an observation study on an existing rooftop garden in Singapore and compared surface temperatures on both sides of the roof structure measured in six locations with various foliage densities and LAI. They found the thicker the foliage, the lower the temperature under the vegetation layer became. Fang (2008) tested the shading effect of eight plant species with various heights, leaf thickness and foliage establishment in a controlled experiment. The results echoed the findings of other studies showing the temperature reduction rate under the foliage canopy to be positively related to plant coverage ratio and total leaf thickness. The denser foliage increased the area of shadow underneath it and thicker leaf coverage showed greater thermal resistance, both of which reduced the transmission of solar radiation.

Yamada et al. (2004) compared the performance of green roofs with and without plants in a field experiment, and found that the absence of plants decreased the effect of vegetation in reducing heat gain.

The above results demonstrate the vital role of plants and foliage mass in providing shading and reducing the temperature under the canopy in warm periods of the year, although the impacts in cold climates have not yet been fully investigated.

Moisture content within substrate

Results of both field measurements and laboratory experiments suggest that the moisture level within a substrate is strongly related to the evapotranspiration rate and also the thermal conductivity of a vegetation layer (Arima et al., 2005, Jim and Peng, 2012).

Lazzarin et al. (2005) took field measurements to evaluate the passive cooling potential of green roofs with a focus on the evapotranspiration effect in summer in Vicenza, Italy. Data collected in the driest and wettest periods was later used in calculations for heat flow through the vegetation layer using simulation software TRNSYS. The results showed that heat loss through the wet green roof was more than double of the dry green roof. When compared to a conventional roof (concrete slab plus 40mm insulation layer), the wet green roof reduced incoming heat flux by 90% and the dry green roof by 59%, indicating the increased evapotranspiration rate of the wet green roof helped in reducing the heat transferred through the vegetation layer reaching the roof surface in summer (Figure 3.5).

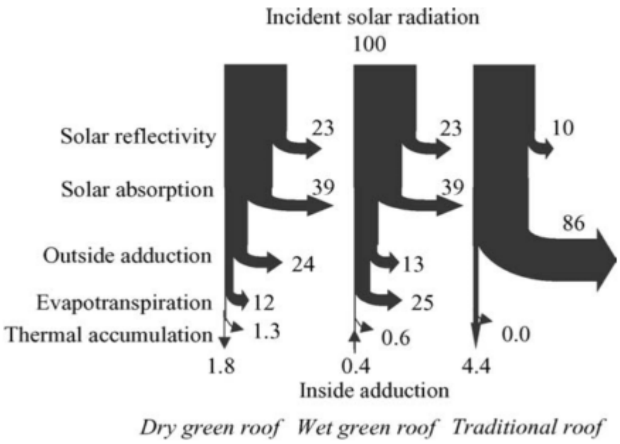


Figure 3.5 Comparison of the heat exchanges within the dry and wet green roofs in summer (Source: Lazzarin et al., 2005)

The evaporative cooling of vegetation can, however, provide adverse effects in cold periods of the year. Lazzarin et al. (2005) found that the wet roof increased heat loss through the insulated roof structure. Wong et al. (2003b) reviewed the impact of soil moisture content on the insulating performance of a green roof and stated that the thermal resistance of green roof layer increased by 0.4m^2K/W per additional 100mm of dry clay soil, whilst it only increased by 0.06m^2K/W for the same soil with 40% moisture content, indicating the diminished insulating performance in wet conditions.

Sailor et al. (2008) conducted laboratory experiments and measured thermal conductivity, specific heat capacity and albedo (solar radiation reflectivity) of eight substrate samples in varying compositions. They found that values of all three parameters varied significantly depending on both substrate composition and the moisture level within the soil. Specific heat capacity and albedo were consistently higher for dry samples and the values decreased as the moisture level increased. Thermal conductivity of the substrate, on the other hand, generally increased as moisture was added to the samples, ranging from 0.25–0.34W/(m·K) for dry soil and 0.31–0.62W/(m·K) for wet soil, further indicating the reduced insulating properties of wet green roofs in winter.

Construction of roofs and walls

Castleton et al. (2010) reviewed existing studies on the thermal benefits of green roofs and found that the impacts of vegetation were largely influenced by the construction of tested roofs. Arima et al. (2005) reported that in an observational study, the impacts of green roofs became negligible beyond an insulation layer laid between the vegetation and the roof slab, and undetectable inside the building. A simulation study conducted by Niachou et al. (2001) indicated that the energy saving potential of a green roof could vary from 2% for a well-insulated roof with U-value of maximum 0.4W/m^{2}K to 31–44% for a roof with no insulation (U-value of 7.76–18.18 W/m^{2}K). Saki et al. (2006) conducted similar analysis using numerical models and found that compared to an uninsulated roof, the potential reduction of air-conditioning load due to a green roof in summer became less than half when the roof had a 25mm insulation layer, and the impacts of vegetation became negligible on a roof with 50mm insulation. While all the above cases were carried out in subtropical and Mediterranean climates, Feng and Hewage (2014) assessed the performance of green roofs and walls on a LEED Gold standard building in the continental climate of Canada employing building simulation software, DesignBuilder and EnergyPlus. They found vegetation systems not to be a cost-effective solution in reducing energy loads of an already high performing building.

The above studies all suggested that green roofs and walls would be more effective in improving the thermal performance of building envelops with a low thermal resistance compared to a well-insulated structure of current standards. In fact, Castleton et al. (2010) recommended that from an energy saving perspective, the true potential of green envelopes would lay in retrofitting to improve existing building stock in the UK where half of all properties were built before 1965 when no insulation standards were implemented within the construction industry.

However, findings from other studies have indicated minimal or even adverse effects of vegetation on the insulating performance of envelopes. For example, Yamada et al. (2004) compared the performance of a green roof against an externally insulated roof during a field experiment and concluded that conventional insulation materials would be more beneficial in increasing the thermal resistance of a roof in winter with green roofs being beneficial in reducing undesirable heat flow in summer, particularly in subtropical and tropical climates. They reported that the green roof reduced heat gain and increased heat loss in summer compared to the external roof insulation as its high thermal resistance prevented heat from being released through the structure. In winter, green roofs showed significantly higher amounts of heat loss through the roof slab compared to the insulated roof. Moreover, Saki et al. (2006) observed the green roof adversely increased the amount of heat loss through both insulated and uninsulated roofs during a Japanese winter. Such results raise the question as to whether a ‘vegetating’ approach is a viable alternative to conventional insulation materials in regions where energy demand is predominantly for heating.

3.3. Conclusion

In this chapter, existing studies and findings that are most relevant to the present thesis were reviewed, and the following conclusions drawn.

- Green roofs and walls moderate daily temperature fluctuations on a building's surface by mostly reducing daytime peak temperatures.

- By minimising the influence of variable outdoor conditions on a building's surface, vegetation cover decreases heat transferred through a building external structure.

- Not all systems provide the same thermal impacts. Influential factors for green roof performance include: foliage mass and coverage, thickness and moisture level of substrate; and for green walls: system configuration and compass orientation of the wall.

As with any external insulation material, the original construction of a building determines the degree of thermal improvements a green cover can provide, meaning less impact on a better performing envelope. Many findings from both experimental and theoretical studies imply that climatic factors greatly influence energy load reductions green roofs and walls can deliver; however, previous field studies were concentrated in the humid subtropical and tropical climates of Asia, and the Mediterranean climate, most only covering the summer period. Therefore, physically measured data in other climates including seasonal variations are required to evaluate the thermal performance of vegetation systems throughout a year and to also validate existing simulation results as Perez et al. (2014) concluded in a recent review on the subject.

4. Thermal monitoring of a green roof

Field experimentation was conducted to quantify the impacts of green roofs on the thermal performance of buildings in the UK. The study also focused on investigating the influence of a substrate thickness on the thermal performance of vegetation systems. Following the introduction of previously conducted field studies and the knowledge gained from such studies explained in Section 4.1, the methodology of the experiments carried out for this study are introduced in Section 4.2 with the description of the tested roof and measurements taken. The results of temperature measurements are presented in Section 4.3, and then the impacts of green roof cover on building thermal conditions within the UK climate are discussed in Section 4.4. The key findings of the field study are presented in Section 4.5.

4.1. Introduction

A number of existing studies have verified the effects of green roofs in reducing roof surface temperatures in summer. Extremely high daily maximum temperatures on the conventional roof surface around 54–70℃ were observed in those studies and green roofs reduced this by 22–35℃ (Liang and Huang 2011; Liu and Baskaran 2003; Sonne 2006; Spolek 2008). The cooler roof surface meant less heat gain through the structure and some researchers found that green roofs reduced the total heat flow in summer by 72–95% (Liu and Baskaran 2003; Spolek 2008). This consequently decreased both internal roof (ceiling) surface and indoor air temperature as demonstrated in studies conducted in Japan (Ochiai et al. 2006; Saki et al. 2006; Sano et al. 2001).

There have been fewer studies looking at the effects of vegetation systems in winter. In general, these studies found green roofs increased the daily minimum temperature of both sides of the roof surface and the indoor air temperature by a few degrees in a cold period of the year in the respective climates where experiments were conducted (Saki et al. 2006; Simmons et al. 2008).

These studies were mostly carried out in humid subtropical or tropical climates where considerably higher temperatures and much higher solar radiation were experienced in summer compared to the UK. The exception to these were experiments conducted by Liu and Baskaran (2003) in Ottawa, Canada and Teemusk and Mander (2009) in Tartu, Estonia, both within a humid continental climate. Their findings in summer were in line with other studies; however, winter results were still not completely applicable to the UK climate as both reported negligible impacts of green roofs due to heavy snow cover over a few months in winter when the average minimum temperature in the coldest month was -8.2℃ in Tartu and -14.8℃ in Ottawa, significantly lower than the UK average of 0.8℃.

Thus, in this study, field experimentation was carried out to evaluate the effects of green roofs on the roof surface temperature and indoor air temperature throughout four seasons in the maritime temperate climate of England, UK. Since a number of studies suggested the substrate mass can directly influence factors that determine the cooling and insulating effects of vegetation including the evapotranspiration rate and thermal resistance of soil (Iwayama and Tarumi 2006; Suzuki 2008; Yamada et al. 2004), the study also focused on investigating the influence of substrate thickness on the thermal performance of green roofs.

4.2. Experimentation

The experiment was carried out on a green roof consisting of vegetation with substrate layers of varying depths in Meltham, West Yorkshire, England. The green roof was installed in the autumn of 2010, and the thermal monitoring commenced in January 2011. Analysis was carried out on the data collected during a 31-month period until July 2013.

4.2.1. Green roof

The monitored green roof was built on a two story building owned by research partner, ABG Ltd. Vegetation covered a third of the approximately 30x30 meters roof on an old industrial building utilised as a warehouse.

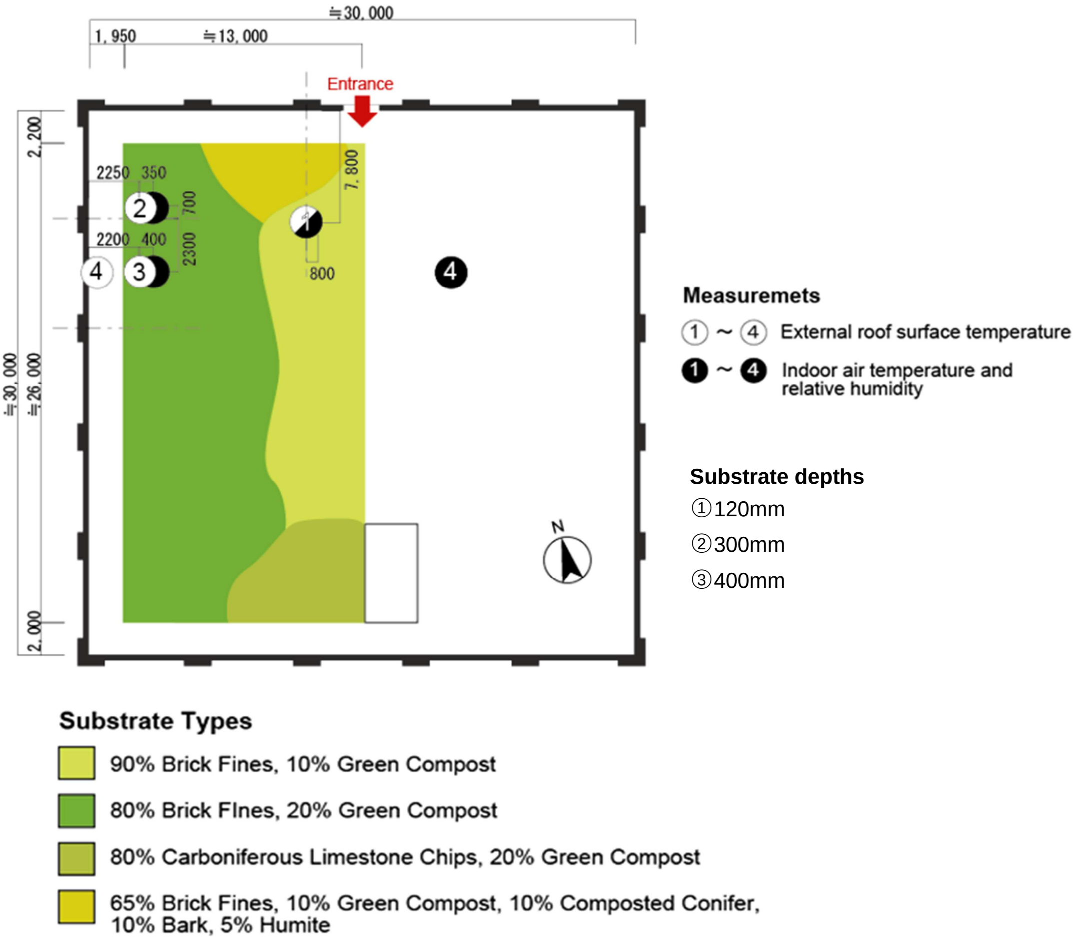


Figure 4.1 Roof plan, substrate composition and location of thermal sensors

The depth of the substrate layer varied between 100mm to 450mm and the surface was gently sloped from the southwest edge to the east (Figure 4.1). The green roof was unevenly divided into four sections, each with a different type of growing medium laid to support various plant systems. The majority of the area consisted of crushed bricks and compost in different ratios with the exception of the southeast corner of the roof which was designated for calcareous plants. Temperature measurements were taken at three locations that shared a similar composition of growing medium. The vegetation was planted between autumn 2010 and spring 2011 at each measured point with the following themes.

① Sedum (substrate: 100mm)

② Perennials (substrate: 300mm)

③ Wildflower meadows (substrate: 400mm)

Figure 4.2 Various planting themes on the locations where temperature sensors were placed

In August 2011, the first summer in the plants cycle, vegetation was established to cover about half of the green roof area; locations ① and ③ generally had a larger ratio of plant coverage compared to ②. The vegetation on the roof established itself over the first couple of years, the majority of plants became dormant during winter and early spring then regrew in summer, providing continuous foliage cover.

Figure 4.3 Monitored green roof in April (left) and August 2012 (right)

4.2.2. Observed building

The building used for the observation study originally had five stories before the top three floors were demolished. Both 100mm screed and insulation boards were laid under a waterproof membrane to provide durability and thermal insulation to create a roof on what was initially the third floor. The inside of the building was used as a large warehouse and there was no partition within this space.

Figure 4.4 Exterior and interior views of the monitored building (2010)

The monitored building was situated in Meltham, UK, a town located at 53°35'N1°51'W within a maritime temperate climate z one which is relatively mild, though weather conditions are largely influenced by its high altitude and exposed position on the edge of the Pennines. Due to these conditions, Meltham experiences a high amount of rainfall compared to other parts of the UK with an average annual rainfall of 1,028mm. The coldest month is usually February with an average minimum temperature of 0.5℃, July being the warmest month with an average da ily maximum temperature of 20.1℃ (Met Office 2014).

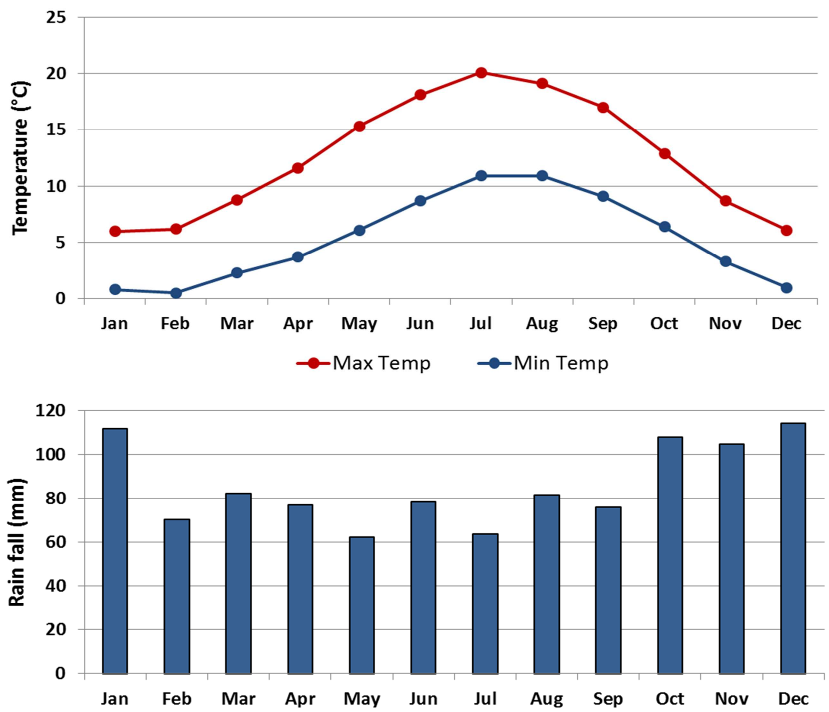


Figure 4.5 Monthly average daily maximum and minimum temperatures (top) and total rain fall (bottom) in Meltham (Source: Met Office 2014)

4.2.3. Measurements

Thermal sensors were placed in three different locations under 120, 300 and 400mm substrates to measure the roof surface temperature. Air temperature and relative humidity loggers were attached to the ceiling corresponding to the location of the external sensors to measure ambient air temperature near the ceiling under the green cover. Temperatures of the non-vegetated part of the roof were also measured for comparative analysis. The original roof consisted of 100mm insulation and 100mm screed layers on top of the 100mm concrete slab (Figure 4.6). Measurements were recorded on a data logger at 20 minute intervals.

A weather station was installed onsite by ABG Ltd six months after the commencement of the study to provide vital weather records; however, a large part of the data over the observation period was unfortunately lost due to technical errors resulting from a direct lightning strike to the equipment.

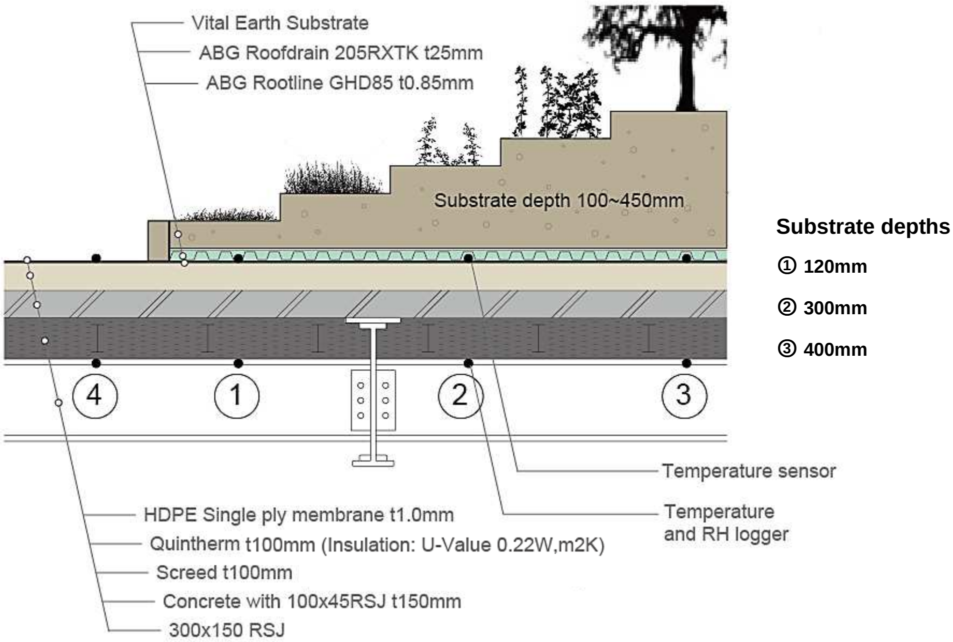


Figure 4.6 Schematic section of the green roof and the location of thermal sensors

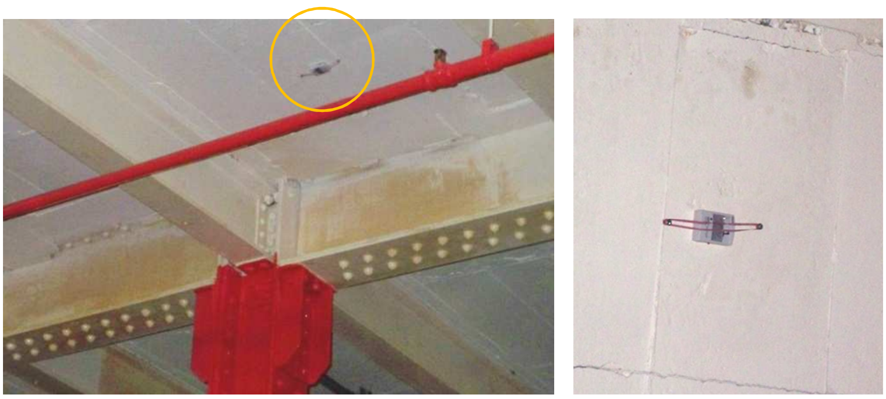


Figure 4.7 Temperature and humidity logger mounted on the ceiling under the green roof to measure ambient air temperature

Limitations of the field experiments

The internal temperature loggers were measuring the ambient air around the ceiling and not the contact surface temperature; also, external measurements were taken on the surface of the waterproof membrane rather than the roof structure itself as it was not viable to cut through the membrane to insert thermal probes. This could have compromised the accuracy of measurements compared to the method of mounting thermal sensors directly on the building surfaces.

The thermal monitoring of living components on the building surface proved challenging and particularly taking outdoor measurements. The equipment including thermal sensors, loggers and the weather station all developed some type of fault over the observation period due to either extreme weather conditions or human and manufacturing factors and errors. There was a lack of consistent data over the observation period from the outdoor data logger. This was due to faults within the logger caused by extremely low temperatures in the winter of 2010 and water ingress in the summer of 2011. Accidental damage to temperature sensors also occurred during maintenance provided by ABG Ltd in 2012. Thus, the analysis in this chapter was carried out mostly on temperature data from the internal loggers recorded between November 2010 and July 2013, and nine months of outdoor observation data collected from November 2012 to July 2013. Acquisition of further data sets may be required for a more comprehensive analysis.

4.3. Results of temperature observation

Since there were some unusual external temperature readings from the 300mm substrate during the summer 2013 and the recorded temperatures under the two thicker substrates showed generally insignificant differences from each other, the external temperature analysis was carried out by focusing on a comparison between 120mm (semi-intensive green roof) and 400mm (intensive green roof).

4.3.1. Summer

In July 2013 which was the sunniest and warmest month of the entire observation period, the monthly average temperature was 18.3℃ and a maximum temperature of 28.6℃ was recorded on the 9th July. Overheating on the exposed roof surface occurred on most days within that month, and this can be seen as sharp spikes on the 'No Veg' graph in Figure 4.8.

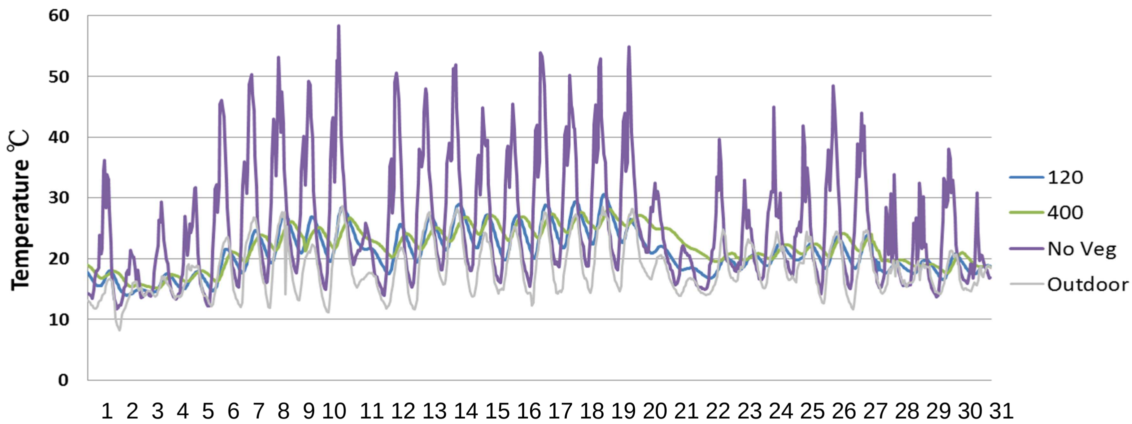


Figure 4.8 Recorded roof surface temperatures under three sections of the green roof in July 2013

Figure 4.9 shows that on the hottest day (9th July), the exposed roof surface reached a height of 58.4℃ whilst both 120 and 400mm green roofs prevented the roof surface from overheating due to solar radiation during the day, and also delayed heat reaching the surface by approximately two hours (120mm) and six hours (400mm) respectively. However, they also showed an adverse effect in insulating the roof at night, preventing the heat escaping through the roof surface while the exposed surface cooled quickly along with the outdoor air in the evening. The roof surface under the 400mm vegetation was kept 5.8–9.7℃ warmer at the coolest time of the day during those three days.

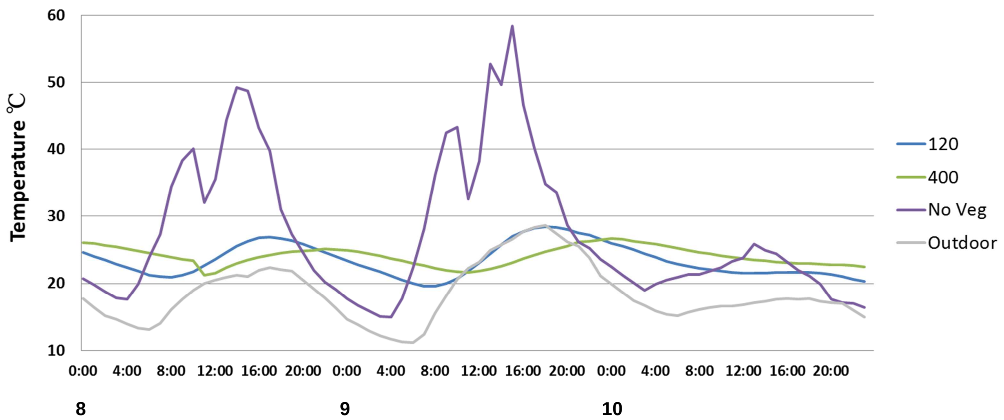


Figure 4.9 Recorded roof surface temperatures under three sections of the green roof between 8–10th July 2013

Over the month of July, the green roof significantly reduced daily temperature fluctuation occurring on the exposed roof surface mostly by decreasing the daytime temperature but also slightly increasing the night-time temperature. Roof surface temperatures under the 400mm substrate fluctuated less compared to the 120mm layer due to the extra insulating effects provided at night. On average, the green roof reduced daily peak surface temperatures by 12℃ and increased the minimum temperatures by 2.4-5℃ (Figure 4.10). The insulating effect of the thicker green roof had a negative impact in warm weather as it prevented heat escaping from the internal space through the roof structure, and the 400mm green roof kept the roof surface temperature 5℃ warmer on average than the exposed roof during the night.

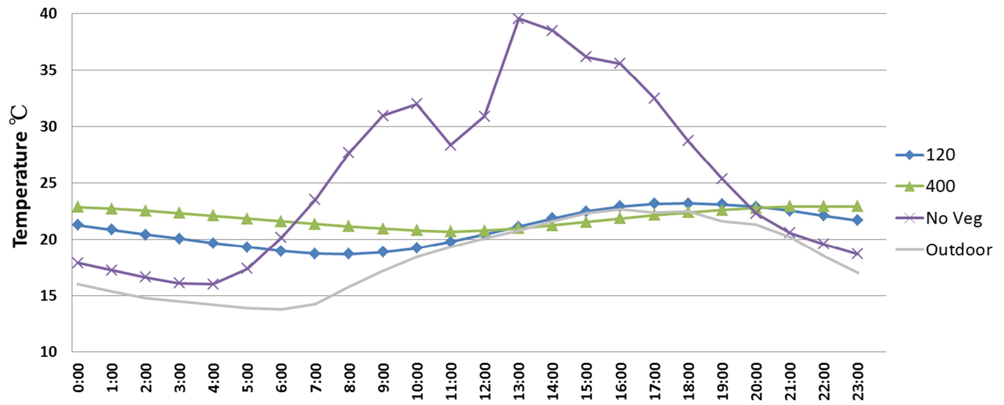


Figure 4.10 Hourly mean roof surface temperature over the month of July 2013

The impacts on indoor air temperature were marginal throughout the observation period and the difference in hourly mean temperature among the four measured locations was often within 0.5℃. This could be due to the effect of roof insulation stabilising the indoor air and consequently reducing the impacts of the vegetation cover. In general, the temperature under the 120mm green roof was similar to the non-vegetated roof, and the temperature under the thicker green roofs stayed 0.2–0.4℃ higher than the other two in summer (Figure 4.11).

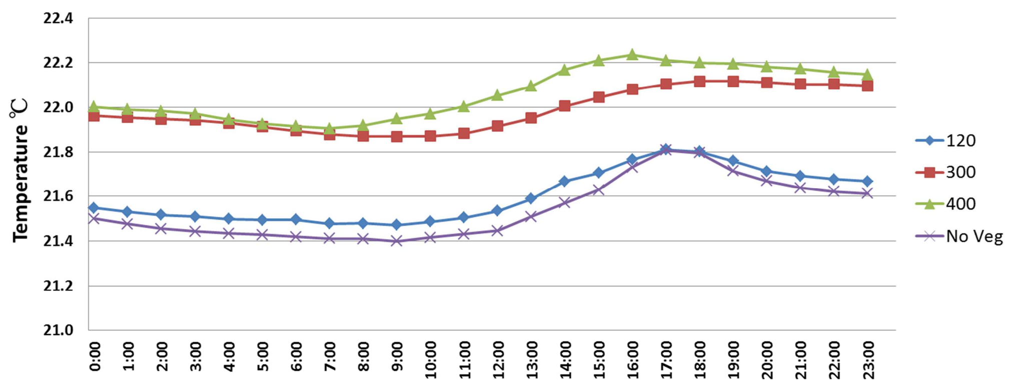


Figure 4.11 Hourly mean indoor temperature over the month of July 2013

4.3.2. Winter

Overheating on the non-vegetated roof surface was also observed on bright winter days which caused fluctuations in daily membrane temperatures as demonstrated in Figure 4.12.

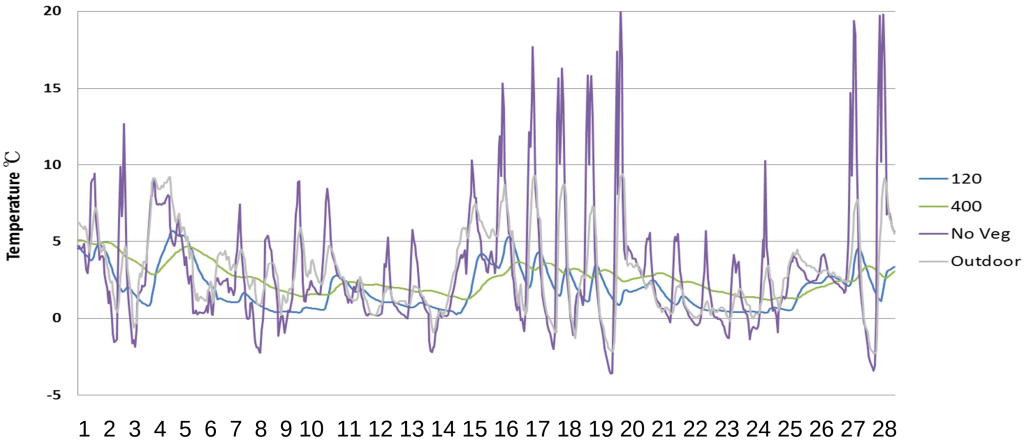


Figure 4.12 Recorded roof surface temperatures under three sections of the green roof in February 2013

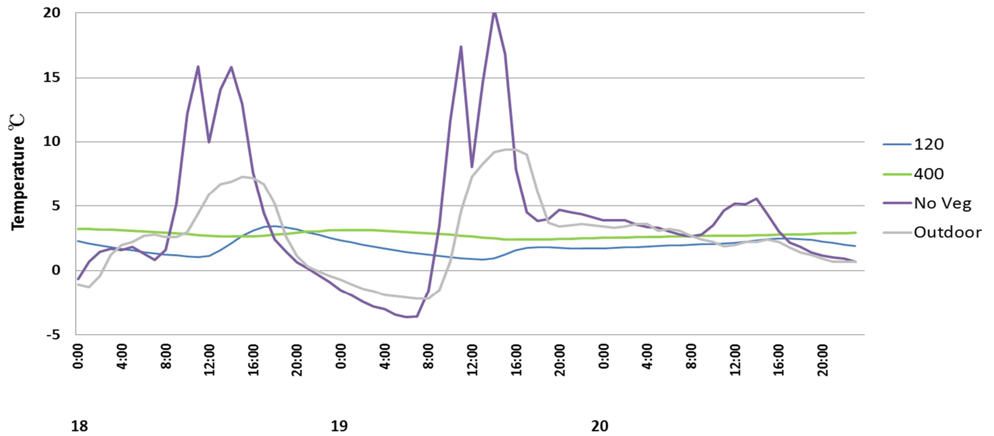


Figure 4.13 Recorded roof surface temperatures under three sections of the green roof between 18–20th February 2013

The thick substrate almost eliminated outdoor influences on the roof surface and kept its temperature constant throughout bright sunny days (18th and 19th) and also on a cloudy day (20th). The 120mm green roof had similar effects although the membrane temperature fluctuated slightly, indicating the influence of solar radiation and outdoor temperature reaching the roof surface under the thinner vegetation layer (Figure 4.13).

Over the month of February 2013, the coldest month during the observation period with an average outdoor temperature of 6.6℃, the green roofs stabilised the roof surface temperature by decreasing peak temperatures and increasing the minimum temperature. On average, the green roofs reduced daily peak temperatures on the roof surface by 5.4–5.7℃ and increased the minimum temperatures by 0.9–1.8℃ (Figure 4.14).

Similar to the summer results, the differences in external surface temperatures were not directly translated into the internal measurements. The temperature differences were only marginal although the green roofs increased the ambient air temperature near to the ceiling by an average of 0.2℃ throughout the day in winter (Figure 4.15).

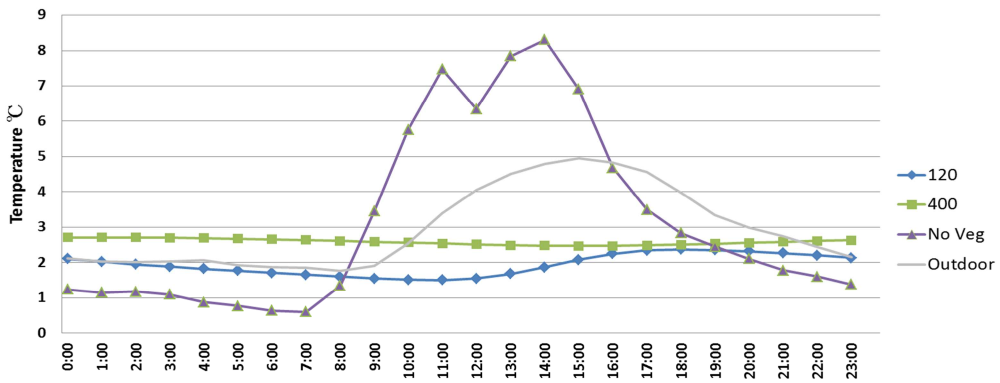


Figure 4.14 Hourly mean roof surface temperatures for the month of February 2013

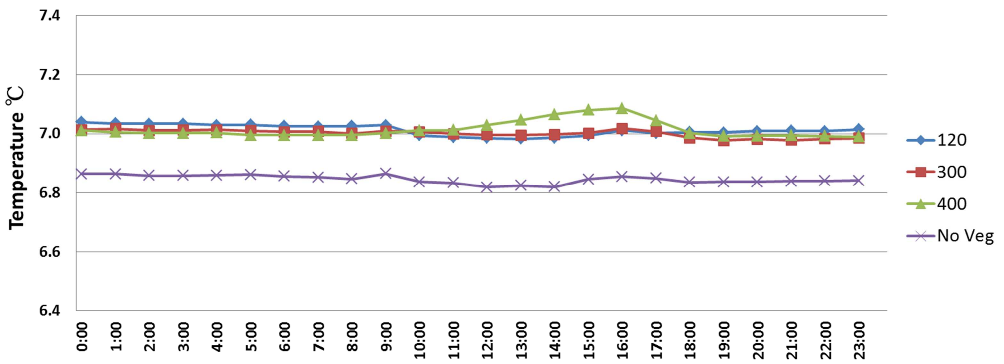


Figure 4.15 Hourly mean indoor temperatures for the month of February 2013

4.4. Discussion

Effects on roof surface temperature

The surface temperature of the non-vegetated roof fluctuated daily regardless of season as it was influenced by solar radiation during the day and cold temperatures at night. The exposed roof surface was noticeably overheated in the afternoon on bright summer days when the surface temperature reached over 50℃. Green roof layers minimised the influence of the elements and regulated the roof surface temperature throughout a day. On average, green roofs reduced daily peak temperatures of the roof surface by approximately 12℃ in the warmest month with an average outdoor temperature of 18.3℃. The reduction was slightly less compared to previous studies which were 22–35℃. This is due to most of those existing studies being conducted in subtropical climates, experiencing much higher temperatures and solar radiation exposure in summer compared to Meltham, UK, with some recorded higher peak temperatures on the roof surface around 70℃ (Liang and Huang 2011; Liu and Baskaran 2003; Sano et al. 2001; Simmons et al. 2008; Sonne 2006). Vegetation also delayed the time of peak temperatures by two to six hours by slowing radiation heat from reaching the roof surface. This effect was more significant in the green roof with a thicker substrate. These results were in line with the reports of Simmons et al. (2008) and Spolek (2008) who observed the same peak temperature delay of 1–3 hours for a 100mm green roof and 4–6hours for a 150mm green roof respectively.

In the winter months, green roofs increased the minimum roof surface temperatures by 0.9–1.8℃; lower than the figure of 2–5℃ observed by Simmons et al. (2008) on a day when the minimum outdoor temperature was around 5℃ in Austin, USA. The difference can be explained by colder and wetter winter months in Meltham, UK, with twice as much precipitation and an average minimum temperature of near to 0℃. This means higher moisture levels within the substrate which would consequently reduce the thermal resistance of green roofs as previous studies have found (Lazzarin et al. 2005; Sailor et al. 2008).

The observation results also indicated a potentially undesirable effect on roof surface temperatures with a vegetation cover. The green roofs increased the mean daily minimum temperature for the warmest months by 2.4–5℃. Sano et al. (2001) also recorded an average 2℃ increase in roof surface temperatures at night in Yokohama, Japan, and Sonne (2006) observed an average increase of 7℃ in Orlando, USA . This could become a factor that would adversely reduce radiating heat released through the roof in regions with a high energy demand for air-conditioning. The green roofs also decreased daily peak temperatures of the roofs surface in winter by an average of 5.5℃. The cooler external surface can increase daytime heat loss through the roof in geographical regions such as the UK where energy demand is predominantly used for heating as indicated in the results of the numerical study conducted by Saki et al. (2006).

Effects on the indoor air temperature

The differences in indoor air temperature among all four measured points were marginal. This was due to the 100mm insulation layer (U-value: $0.22W/m^2/K$) within the original roof construction which reduced the impacts of the green roofs. Some studies have found that the effects of vegetation become negligible on highly insulated roofs (Castleton et al. 2010; Niachou et al. 2001). Green roofs increased the ambient temperature near to the ceiling by 0.2–0.4℃ throughout the year by providing additional insulation and reducing heat lost through the roof structure.

Ranson (1991) stated that the optimum room temperature for a residential space is between 20℃ and 22℃. Although the monitored building was utilised as a warehouse and did not have consistent occupancy, the comfort zone of the indoor temperature was set within plus minus two degrees of Ranson's range (18℃ to 24℃) for the pu rposes of this study.

During the summers of 2011 and 2012, there were only two days that the average hourly temperature exceeded the optimum range of 22℃. The indoor temperature of any of the four measured points never exceeded 24℃. Figure 4.16 indicates that in the current cli mate in Meltham, UK, green roofs may have positive effect in keeping the indoor temperature higher as the overall temperature range did not often rise beyond the stated comfort range.

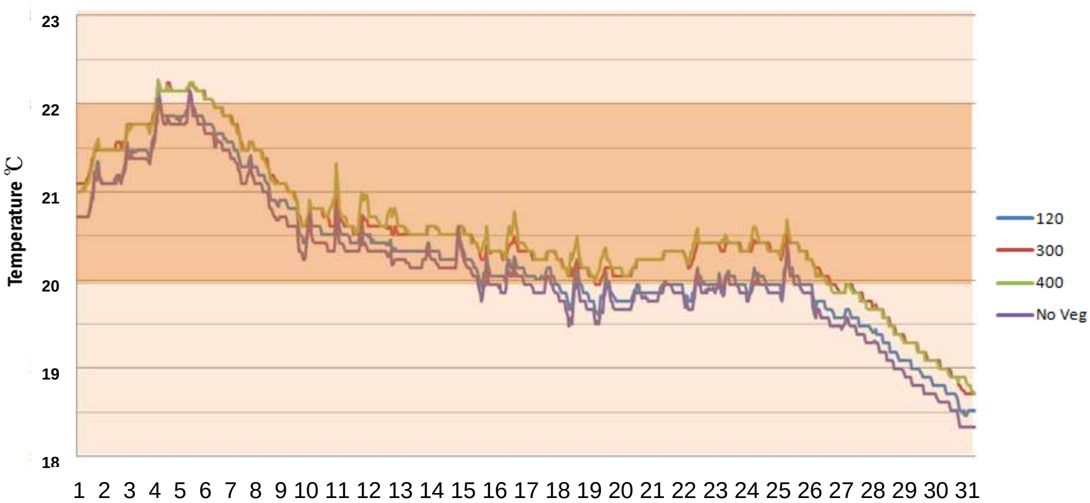


Figure 4.16 Recorded indoor temperatures under four sections of the roof in August 2010

The summer of 2013, however, was warmer than the previous two years. Figure 4.17 shows that in the hottest month of the observation period (July 2013), the indoor temperature exceeded the optimum comfort range for more than half of the month. During this period, 300 and 400 mm green roofs increased the indoor air temperature by 0.6℃ compared to the non-vegetated and 120mm green roof sections.

Results of thicker substrates in UK summer conditions contradict previous findings of green roof studies reducing both the ceiling surface and indoor air temperatures by around 1℃. Since the substrate thickness of the observed green roofs in existing experiments ranged from 100–150 mm (Ochiai et al. 2006; Sano et al. 2001; Simmons et al. 2008), the result suggests that an increase in thickness of the layer of growing medium increased the thermal resistance of the green roof and provided an unwelcome insulating effect in summer. A large mass of substrate prevented heat being released from the roof surface and consequently increasing the air temperature under the roof. This echoes the findings of Yamada et al. (2004) who stated a green roof with 75mm substrate showed better performance in reducing temperatures of the inner roof slab surface compared to a 150mm green roof in summer by providing similar temperature reductions during the day with less adverse insulating effects than the thicker green roof provided at night.

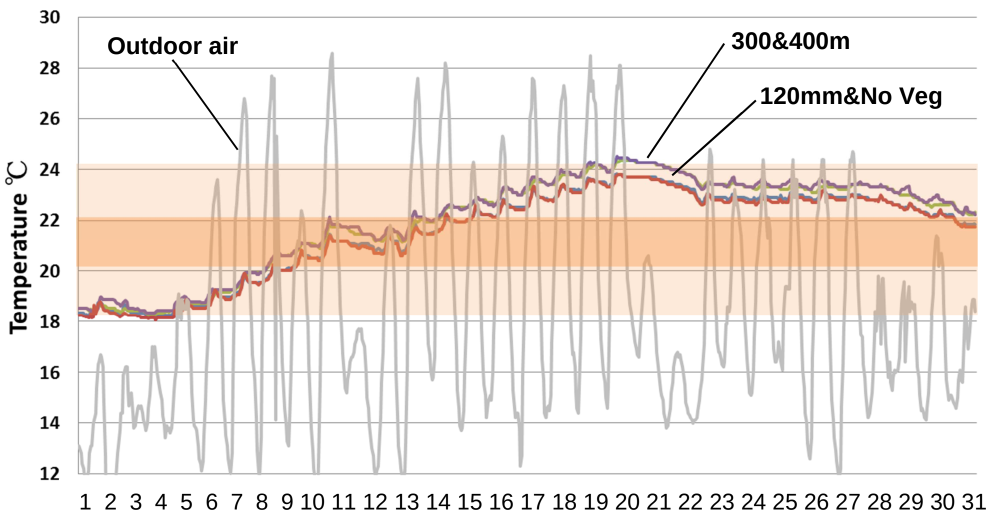


Figure 4.17 Recorded indoor temperatures under four sections of the roof in July 2013

Impacts of the green roofs in different substrate depths

While the 300 and 400mm green roofs increased the indoor temperature in warm periods of the year, the 120mm vegetation showed similar insulation effects to the deeper sections in winter without significant night-time temperature increase in summer (Figure 4.18).

This suggests that from a thermal benefits perspective, extensive and semi-intensive green roofs (substrate depths of 80–200mm), would provide similar thermal benefits in increasing the indoor air temperature in winter and a less negative insulating impact during summer in warmer climates. Intensive green roofs with a depth greater than 200mm on the other hand, would be suitable in places with cooler climates to increase thermal resistance of vegetation and provide insulating effects throughout all four seasons.

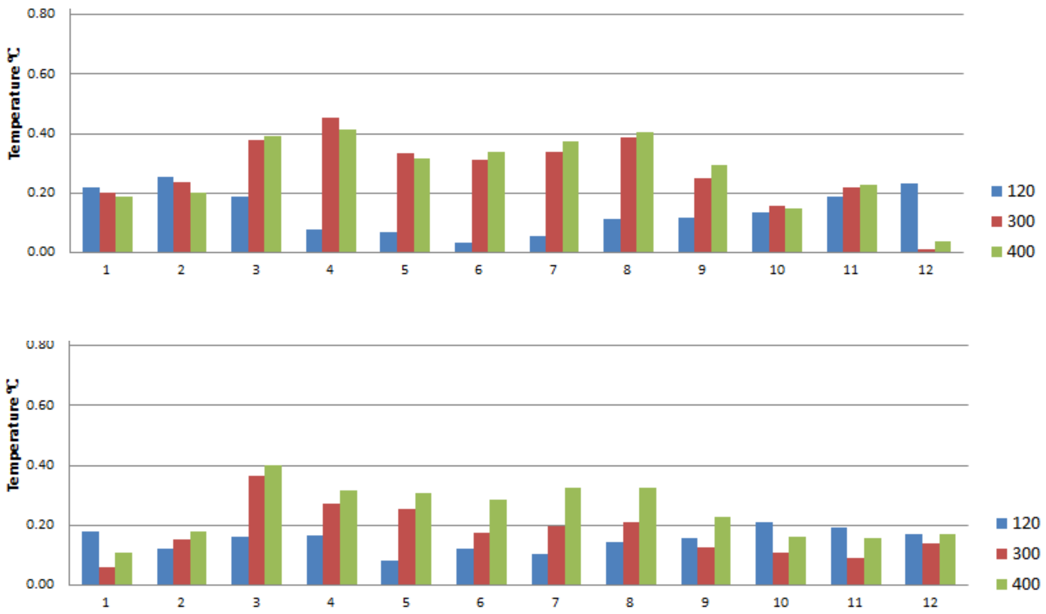


Figure 4.18 Increases in monthly mean indoor temperatures as a result of the green roofs in 2011 (top) and 2012 (bottom)

4.5. Conclusion

This chapter explained the field experimentation and results of analysis using data collected to evaluate the effects of green roofs with different substrate thicknesses on the roof surface and the subsequent indoor air temperature. The main findings of this study are as follows.

- Green roofs regulated the roof surface temperature throughout the day regardless of season, reducing daily peak temperatures of the roof surface by an average of 5.5℃ in the coldest month and 12℃ in the warmest month. (4.3.1 & 4.3.2)

- Green roofs provided insulating effects and increased the minimum roof surface temperatures by 0.9–1.8℃ in the coldest month and also 2.4–5℃ in the warmest month which could have adverse effects in summer. (4.3.1 & 4.3.2)

- Green roofs increased the indoor air temperature near the ceiling by 0.2–0.4℃ throughout the year. (4.3.1 & 4.3.2)

- Since increased substrate mass in the green roof resulted in greater insulating effects, intensive green roofs with a substrate thickness of over 200mm would be suitable in cooler climates and shallower green roofs with less negative insulating impacts during summer in warmer climates. (4.4)

5. Experimentation on the thermal effects of green walls

The aim of this chapter is to evaluate the effects of green wall cover on a wall surface and the indoor air temperatures of a building for a twelve-month period in climatic conditions in Sheffield, UK, by demonstrating experimentation including field measurements using green wall test beds on an actual building. The focus of the study is also to find out factors that could influence the thermal performance of green walls such as system variations, the presence of plants and an extra insulation layer added to the systems.

Following the introduction of previously conducted field studies and the knowledge gained from such experiments explained in Section 5.1, the methodology of the experiments for this study carried out in Sheffield are introduced in Section 5.2 and 5.3, with the description of test bed design, measurements taken and details of the specific building that the study was carried out on. The results of temperature measurements are presented in Section 5.4, and then the impacts of green wall cover on building thermal conditions in the UK climate are discussed in Section 5.5. The key findings of the field studies are presented in Section 5.6.

5.1. Introduction

Several studies investigated the impacts of vegetation on external wall surface temperatures by monitoring two thermally identical sections of a wall when a vegetation system installed to cover one section and the other kept in original condition for comparative analysis. A green façade with climbing plants reduced the daily maximum temperature of the external wall surface by 5.7–8.9℃ and the living walls consisting of a substrate layer by 11.5–16℃ (Chen et al. 2013; Cheng et al. 2010; Eumorfopoulo and Kontoleon 2009; Hayano et al. 1985; Nojima and Suzuki 2004; Wong et al. 2010). Along with system configurations, many studies found the orientation of the wall to be a major influential factor on the overall performance of a green wall (Djedjig et al. 2015; Kontoleon and Eumorfopoulou 2010).

Other studies looked at the impacts of vegetation on the indoor thermal conditions in summer by monitoring two identical shaped and orientated rooms with vegetation covering the wall of one of the observed rooms. Temperatures were usually measured on both external and internal surfaces as well as air inside the rooms. Eumorfopoulo and Kontoleon (2009) monitored the east-facing single brick wall of a six story building over a summer month in Thessaloniki, Greece. Temperature measurements were taken inside two identically sized rooms, one above the other, where the only external wall of the lower floor was covered by climbers. They reported that the climber cover reduced both mean internal surface and indoor air temperatures by 0.9℃. In a similar experiment using hydroponic living wall panels carried out by Cheng et al. (2010) in Hong Kong, heat flow and electricity consumption for cooling were observed along with temperatures inside rooms on two separate floors. Despite the fact that both rooms were air-conditioned in order to maintain the same indoor temperature, the internal surface of the wall with vegetation consistently stayed 2℃ cooler than the original concrete wall.

A surprising number of the studies carried out to date for both green roofs and walls did not specify the internal layout of buildings they observed or clarify potential influences for the indoor conditions of a given building in their results. In order to minimise influential factors such as occupancy and mechanical heating and cooling inside a building, other experiments used purpose built test structures to acquire more accurate thermal measurements. In Tokyo, Japan, Nojima and Suzuki (2004) conducted a field study on a green façade using a portable cabin which contained two small test rooms of approximately $2m^3$ divided by insulated partitions. The monitored south-facing wall consisted of 47mm uninsulated cement panels, partially covered by climbing plants. A similar study was carried out on a compost-based modular living wall by Olivieri et al. (2014) in central Spain.

Both reported average internal air temperature reductions of 4.1℃ and 5.6℃ during a summer month, more substantial compared to the findings of Eumorfopoulo and Kontoleon (2009) on an actual building. Magnified internal temperature reductions were also identified in a green roof study conducted by Simmons et al. (2008) using metal test cabins, and can be explained by the low thermal resistance of the tested envelopes along with the high ratio of roof or wall surface area against the small internal volume.

The above green wall studies were all conducted in subtropical climates with higher temperature and solar radiation exposure compared to the UK. A simulation study carried out by Djedjig et al. (2015) using TRNSYS found that in two studied climates, a 50% reduction in the annual cooling load due to heat flow through the wall was achieved using a living wall consisting of a 150mm organic substrate layer, which was much higher than the heating load reduction of 8.7–11.9%. They concluded the impacts of vegetation would be less significant in a maritime temperate climate similar to London compared to the Mediterranean climate with high air-conditioning loads.

This study, therefore, investigated the thermal performance and impacts of green walls within the UK climate and specifically Sheffield, England, by acquiring physically measured temperature data in order to gain a much more complete and comprehensive understanding than previous studies and to validate simulation results. The study also looked at the influence of system configuration on the performance of green walls. The subject has previously been explored by Wong et al. (2010); however, acquired data was limited to external wall surface temperatures as their test beds were installed on a free-standing wall. Also, foliage coverage for the green façade system was not sufficient enough during the observation period to provide viable measurements and data.

Temperature data collected in this field study was later used in numerical studies which analysed the effects of green walls on heat flow through the wall and also energy loads for heating and cooling.

5.2. Experimentation

The field experimentation on green walls was carried out using test beds consisting of three different types of modular living wall systems and a green screen with climbing plants installed on the southwest facing wall of a building in Sheffield, UK. The study was conducted over a twelve month period from December 2012 in order to represent the UK climate throughout all four seasons.

5.2.1. Observed building

The study was carried out in the city of Sheffield located in central England at 53°23’N1°28'W and within the maritime temperate climate zone with mild and maritime weather influenced by the Gulf Stream. Rain falls throughout the year with an average annual rainfall of 835mm. The coldest month is usually January with a daily mean temperature of 4.4℃ and July being the warmest month with a daily mean temperature of 16.9℃ (Met Office 2014).

Figure 5.1 Map of UK showing the location of Sheffield

Green wall test beds were installed on one of the buildings at the University of Sheffield which consisted of two comparable internal spaces sharing a wall of uniform construction to conduct comparative analysis. As well as the internal layout of the building, consideration was also given to aspects including the orientation of a potential wall for the test beds to be installed and also thermal obstructions on the wall. The observed building was selected for its accessible surface without openings facing southwest and with minimum thermal obstructions such as surrounding buildings or vegetation to cast shadows. There were no surrounding structures to cast shadows on the monitored section of the building except for the three story residential block twenty meters away to the west. The orientation of the wall was an important factor in order to include the thermal influence of solar radiation in the study and also to represent standard practice of green wall installation using south or west facing walls to assure plant growth. The monitored wall was also required to be uninsulated in order to investigate the impacts of green walls with and without the presence of an added insulation layer as part of the study.

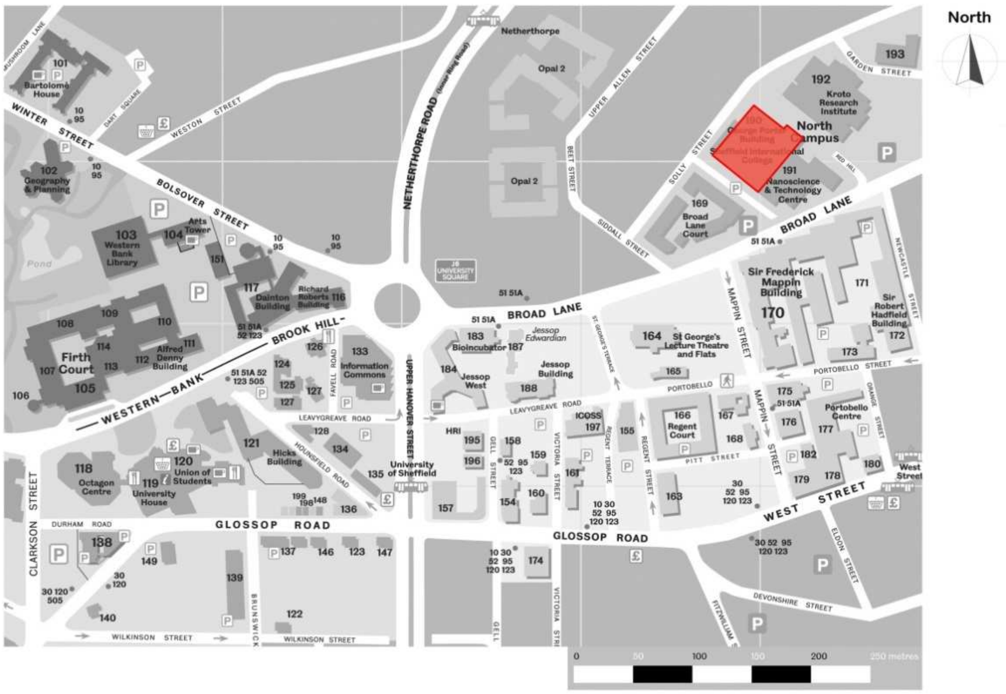


Figure 5.2 Map showing part of the University of Sheffield. The observed building is highlighted in red.

Monitored rooms

Green wall test beds were installed on the southwest facing wall of the observed building. On this part of the building, there was a uniform flat wall of five-stories high without openings, and there were classrooms on the southwest corner of each floor inside the building. Those classrooms were regularly used for teaching activities of up to approximately thirty students at a time during the day throughout any year. The test beds were mounted on the first floor exterior wall corresponding to a classroom inside the building which was identical to a classroom directly above on the second floor.

Figure 5.3 Southwest elevation of the observed building

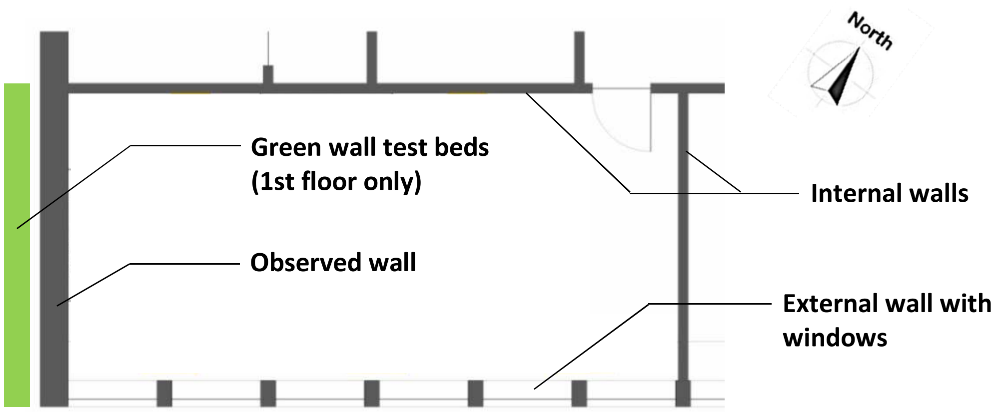


Figure 5.4 Floor plan of the observed classrooms. Green wall test beds were installed to cover the southwest facing wall of the first floor classroom

The building was constructed in the 1960s and both monitored rooms had no alterations or modifications and were in original condition. The observed wall was an uninsulated cavity wall consisting of 100mm brick inner layer and 150mm sandstone block outer layer with 50mm air gap in-between. The southeast elevation of the first and second floor class rooms consisted of a row of single glazed windows with aluminium frames covering 1.75 meters from the ceiling with brick cavity wall from the bottom of windows to the floor and zinc panels on the outside. The other two walls were internal and built of a single brick construction. There were no visible signs of insulation on any of the surfaces in either of the observed rooms (Figure 5.4). Since there was no conclusive information regarding the original building materials and taking core samples to determine the actual construction was not feasible within the time scale of the study, the materials specified above were determined from the CAD drawings created in 1996 and from visual inspections and measurements taken on the actual building prior to this study. The calculated thermal conductivity of the original wall construction was 1.86W/m^{2}K. This is equivalent to the value of a cavity wall without insulation constructed before 1965 when the required standard for a wall was set at 1.7W/m^{2}K in the UK.

Although the two observed rooms were not exactly identical, the room volumes were comparable and they shared the orientation, construction materials, heating regime and occupant activity.

Table 5.1 The dimensions of each classroom

	Width	Length	Ceiling height
1F (with green wall)	4.44 m	9.4 m	2.3 m
2F (reference room)	4.44 m	11 m	2.35 m

Heating regime and occupancy of each room

The University implements a general policy for heating to be on between the period of 1st October and 31st April during any given year. In order to monitor how the heating schedule was managed as well as occupants' behaviours with regards to temperature control, sensors were installed to measure temperatures directly above the wall heaters in both monitored rooms. There were no heaters on the monitored walls in either classroom. The results of this monitoring showed the building mostly followed the University's policy, and the heating time appeared to be set for building occupancy between 8:00 and 18:00.

Occupancy of the two classrooms was monitored by single beam people counters. Both classrooms had a single entry point which was also used as an exit. A beam counter was located in the door way of the respective rooms to count bodies of people walking in and out of the room. The recorded figures were divided by two to determine the number of occupants within the room.

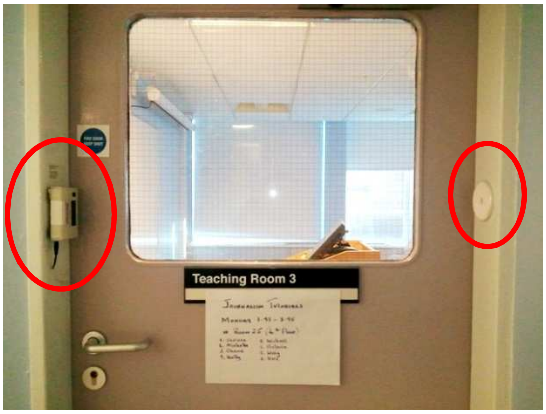


Figure 5.5 A people counter and beam reflector (circled in red) installed at the entrance/exit of the first floor classroom

5.2.2. Limitation of field measurements

Observation was carried out on an occupied building as the purpose of this experiment was to monitor and evaluate the actual thermal performance of green walls on a building that is in use over a twelve month period and specifically in the UK climate. Although the monitored rooms and walls were selected for comparability, there were some factors that could potentially influence thermal measurements which are inevitable in any field experiments using an actively used building.

For instance, the recorded temperature of the external wall surface (without vegetation cover) on the second floor was 0.5–0.8℃ higher than the first floor level between 13:00–17:00 in July, the brightest month of the year during the observation period as demonstrated in Figure 5.6. This could be due to a difference in the level of solar radiation received at a different height of the wall and also the shadow casted over the wall by the three story building twenty meters away from the observed building to the west. These factors may have influenced the results of thermal measurements although the difference indicated in recorded data was marginal. In general, average external surface temperatures of the wall without green cover measured on the first and second floors were comparable and the difference was within 0.4℃ for the entire twelve month period (Figure 5.7).

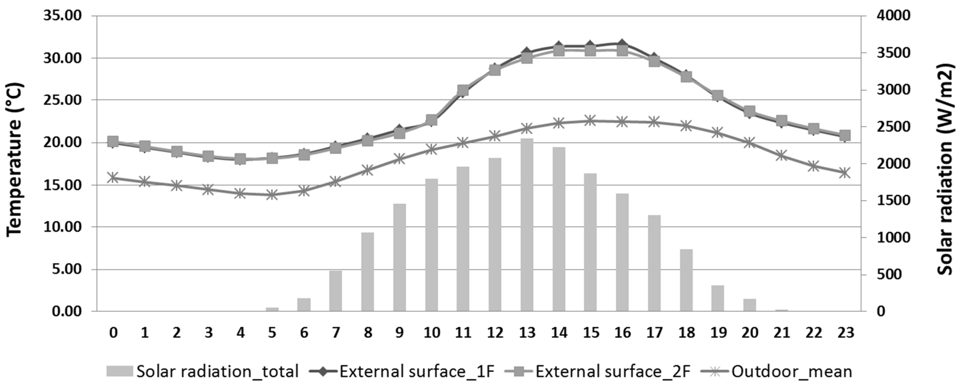


Figure 5.6 Comparison of Hourly mean temperatures measured on the external wall surface of first and second floors in July 2013

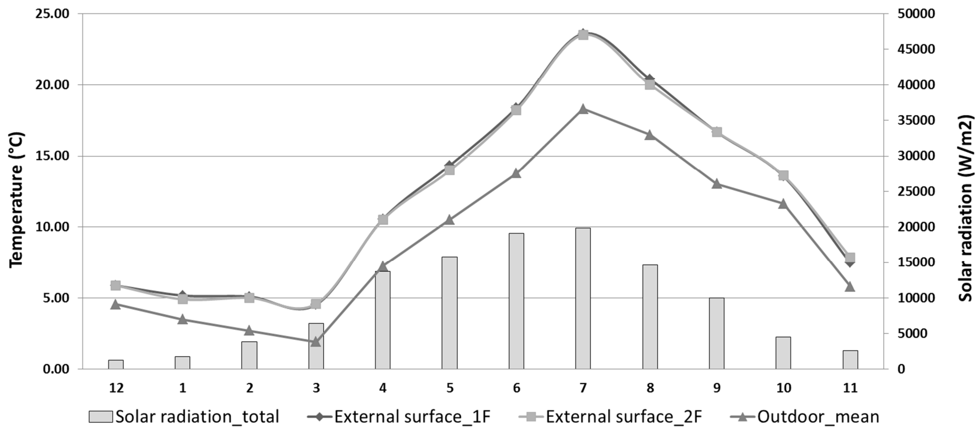


Figure 5.7 Comparison of monthly mean temperatures measured on the external wall surface of first and second floors

The number of occupants and their behaviour were also an influential factor in thermal measurements. The results of occupancy monitoring showed that the first floor classroom with the green wall test bed had an overall 20.3% higher number of occupants compared to the second floor. As both classrooms were mostly occupied between 8:00 and 19:00 for daytime teaching activities, the difference in total numbers for occupancy appeared to be the result in the difference of class sizes (Figure 5.8).

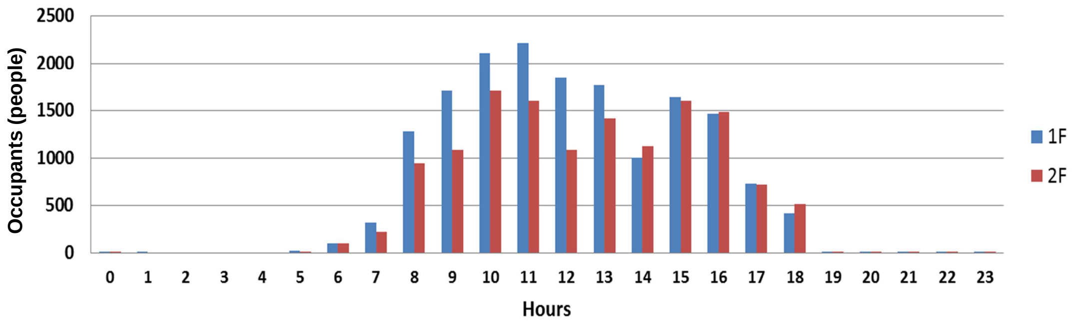


Figure 5.8 Hourly total number of occupants in each monitored room (12 month period)

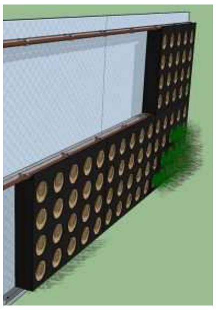
The results of indoor temperature monitoring carried out for a three month period prior to the installation of green wall test beds indicated irregular measurements caused by occupants turning on portable heaters in one of the classrooms. Although the temperature differences in the two classrooms stayed within 1.0℃ for the majority of this period, there were a few occasions that the temperature difference exceeded 10℃. The monitoring of the heating schedule also revealed that the heating was occasionally left on during the night and weekends which made the two rooms thermally incomparable at times.

In order to reduce the effects of occupancy and mechanical heating during the winter period, analysis of the indoor measurements in Chapter 5 and calculation of heat flow in Chapter 6, which required recorded internal wall surface temperatures, were conducted using the data collected during weekends and holidays only when the recorded daily occupancy of both rooms was less than ten and the observed rooms were unheated (See Appendix A). During those periods, there were no teaching activities carried out and all windows and window blinds on the southeast facing wall of the observed rooms were closed to minimise the influence of natural ventilation and incoming solar radiation through the glazing.

5.2.3. Tested green wall systems

Four different widely adopted techniques to cover vertical surfaces with vegetation were selected to be tested in this study in order to investigate and compare the thermal performance of each system. The following table explains commercially circulated living wall and green façade products that represented each type of tested system.

Table 5.2 Specification of four tested green wall systems

Green wall system	Description
Compost 	Product name: ANS living wall (ANS group Europe)
	Module size: H500mm, W250mm, D60mm
	Modular panel system designed to hold organic growing medium in 14 small cells where plants can take root. (ANS Group 2010).
Hydroponic 	Product name: BioWall (Biotecture Ltd)
	Module size: H450mm, W600mm, D80mm
	Panel-based cladding system consisting of plastic panel casings that comprise 80mm thick horticultural Rockwool for plants to root in. It is called a 'Hydroponic' system as it supports plants by the retention of water in the Rockwool without compost (Biotecture Ltd 2014).
Trough 	Product name: Easiwall (Treebox Ltd)
	Module size: H1000mm, W1000mm, D150mm
	A modular unit made from 80% recycled materials designed to appear as vertical planting troughs stacked on top of each other. Each trough can hold a substantial amount of organic growing medium which allows the system to support a wider variety and larger choice of plants compared to other systems (Treebox Ltd 2013).
Ivy screen 	Product name: Green Screen (Hedera Screens Ltd)
	Module size: H2400mm, W1200mm
	The screen consists of a metal grid panel made of 5mm thick galvanised steel wire. It is covered with pre-grown evergreen climbers which are rooted within a container at the base (Hedera Screen Ltd 2014).

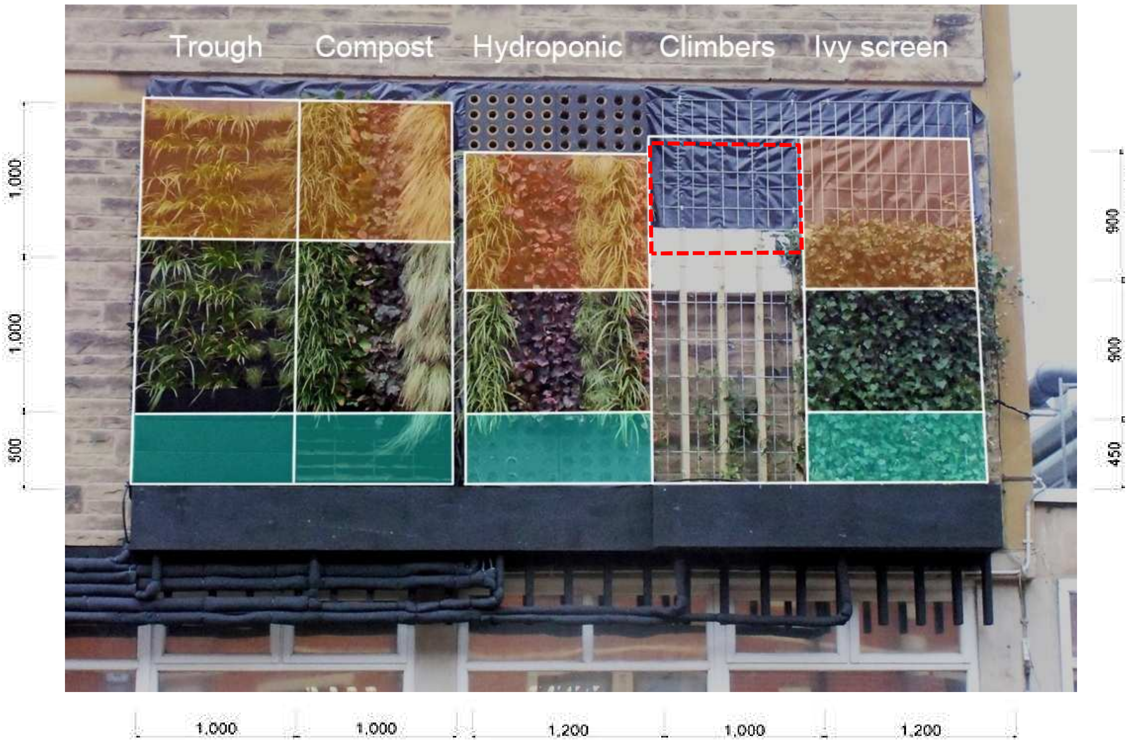
Initial costs and maintenance requirements of green wall systems vary depending on the product as demonstrated in Table 5.3. The described module life span is speculative as the green wall industry is still in its infancy and there have not been enough case studies to accurately estimate how long systems will actually survive. The specified life span of living wall systems used within this study are based on the modular components only and living plants would constantly need replacing during the life span of the system. Living wall systems can sustain a diverse range of vegetation but are also more costly to install and require regular maintenance compared to climber screens. The life span of ivy screens is equal to the standard life expectancy of climbing plants which only require biannual trimming to maintain a desired aesthetic appearance.

Table 5.3 Outline of installation costs, required maintenance and life span which will influence the life-cycle cost of tested green wall systems

	Compost	Hydroponic	Trough	Ivy screen
Installation cost (£/m^2)	450	450	350	160
Maintenance visit (Times/Year)	24	24	12	2
Plants replacement (Plants/ m^2/Year)	6	4	2	N/A
Module life span (Years)	25	25	10 -15	20

5.2.4. The design of test beds

The green wall test beds included three types of modular living wall systems and a climber screen unit as explained in the previous section. Each test bed was horizontally divided into three sections: an original form of the system, the system with an extra insulation layer behind it and a system without plants. All of the test beds were placed inline and created a vegetation cover of approximately 5.5 meters wide and 2.5 meters high.



External insulation layer behind the system

Original form of system

System without plants (Living walls) or less foliage cover (Ivy screen)

Section considered as ‘externally insulated wall’

Figure 5.9 Design of the green wall test beds

Figure 5.9 shows the composition of the test beds and how they were divided into different sections. The top area of each system had 100mm thick Polyisocyanurate insulation board (λ=0.022W/mK) inserted in the gap between the back of the system and the external wall surface of the building. This element was included in the test beds’ design to investigate whether additional insulation would have any impact on the thermal performance of the system and also to explore any potential improvements that could be made on existing products.

All test beds had an original form of each system in the middle section. The study results for this section would clarify the performance of the existing products. They would also become a reference point for the results from the other sections. At the bottom of the test bed, each living wall system had modules without plants, and Ivy screen had an area where there was less foliage cover compared to the middle section. It replicated the conditions when plants failed to establish which would occasionally happen in a real life installation and the results would help understand the impact of plants on the overall thermal performance of the system.

Initially, there was a system named 'Climbers' included in the experimentation which consisted of the same metal grid unit as Ivy screen with plug plants of a climbing species planted at the bottom. It was designed to be a comparison to Ivy screen with pre-grown plants. However, the climbers failed to provide enough foliage cover to deliver viable data within a twelve month. In the numerical studies in Chapter 6, the top section of Climber test beds, which was left as the original wall covered with an insulation board and water proof membrane for the duration of the experiment, was considered to be 'externally insulated wall' (highlighted in red broken lines on Figure 5.9). The data collected from this section was used in calculation to evaluate the performance of external insulation panels by comparing it to green walls. However, the data collected from Climber test beds was excluded from temperature analysis of green walls in this chapter for the reason stated above.

Plants

Plants for living walls and green façades are predominantly chosen with consideration for system type, orientation of wall, local climate and exposure to the elements. Plans for the test beds were selected to represent 'standard' systems for the location and conditions of the monitored wall. Three living wall systems were also considered to share a similar planted theme so that the results of each system would be comparable without being affected by the variation in plants.

Table 5.4 List of species planted in the test beds

System	Plant species
Compost	Berginia, Heuchara, Carex testacea, Pennistome
Hydroponic	Berginia, Heuchara, Carex testacea, Carex golden curls
Trough	Carex testacea, Carex golden curls, Pennistome
Ivy screen	Hedera Herix
Climbers	Lonicera, Crematis

Figure 5.10 Flowers of Berginia (Left) and Carex testacea (Middle) in April and Heuchara (Right) in July, providing seasonal interest on the living walls (2013)

As the test beds were installed in October, plants stayed dormant throughout late autumn and winter; consequently, there were no visible changes in the first few months of the study. In an exceptionally dry April when Sheffield recorded only 9mm of rainfall for the whole month, some plants became visibly stressed and dried out foliage was present on parts of the wall. Damaged plants rapidly recovered in summer and provided around 300mm thickness of uniform foliage mass for the duration of the observation.

Figure 5.11 Test beds in November 2012 (left) and July 2013 (right)

5.2.5. Thermal measurements

Thermal monitoring was carried out for twelve months from December 2012 to November 2013. Temperature data was collected on both exterior and interior wall surfaces, within the vegetation layer and the indoor air of the two monitored classrooms. Temperatures on wall surfaces and inside the vegetation were measured by Type-T thermocouples and measurements were recorded on data loggers. Temperature and humidity loggers were mounted on the walls at a number of different locations inside the classrooms to monitor indoor air temperatures and relative humidity. All thermal measurements were taken at fifteen minute intervals.

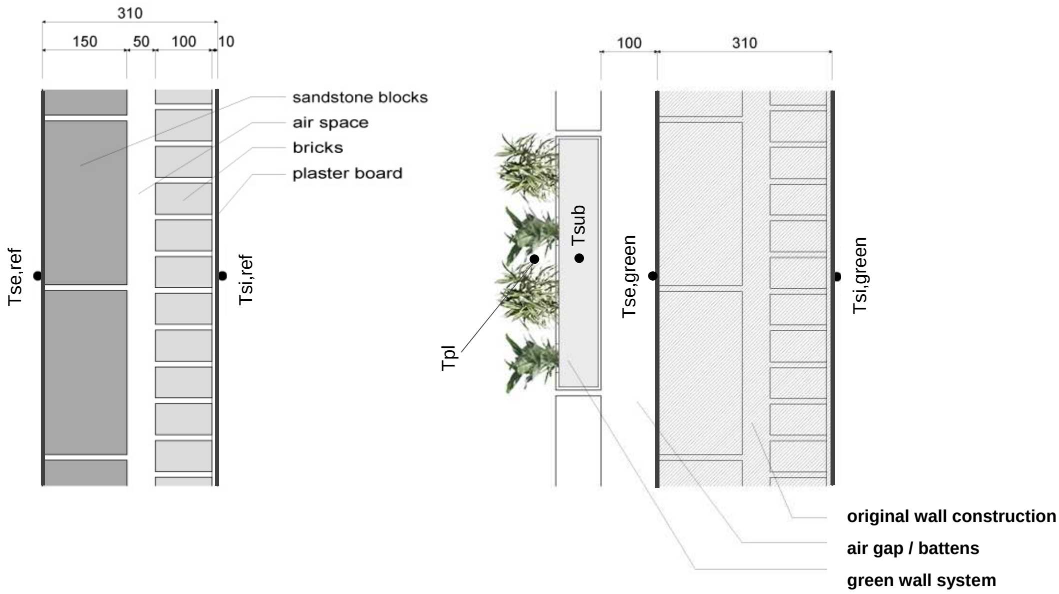


Figure 5.12 Section of the reference wall (left) and typical green wall system (right) showing the locations where each temperature measurement was taken

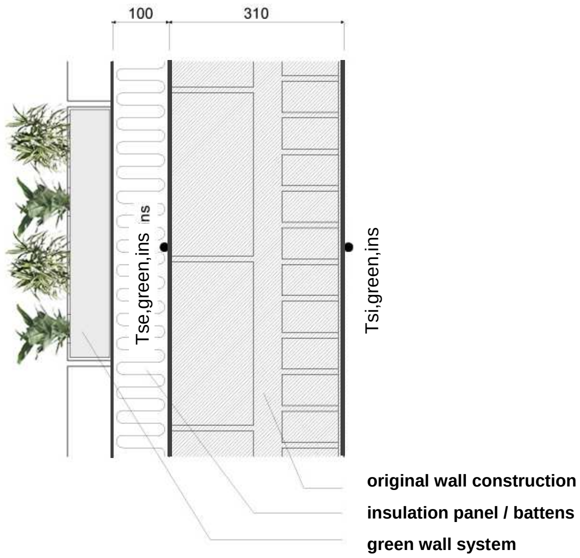


Figure 5.13 Section of green wall system with an added insulation layer. Thermocouples were located behind the insulation to measure the surface temperature of the original wall

There was approximately 100mm of air space between the back of the green wall units and the external surface of the wall where vertical battens were placed for the units to be fixed on (The depth of gap was not uniform due to the uneven surface of the sandstone blocks). In the section of test bed with added insulation, 100mm insulation panel was inserted in this space between the battens and measurements were taken on the wall surface behind the insulation as illustrated in Figure 5.13.

Figure 5.14 Timber battens before test bed installation. Strips of insulation panels were inserted between the battens behind the ‘added insulation’ section of the test beds at the top

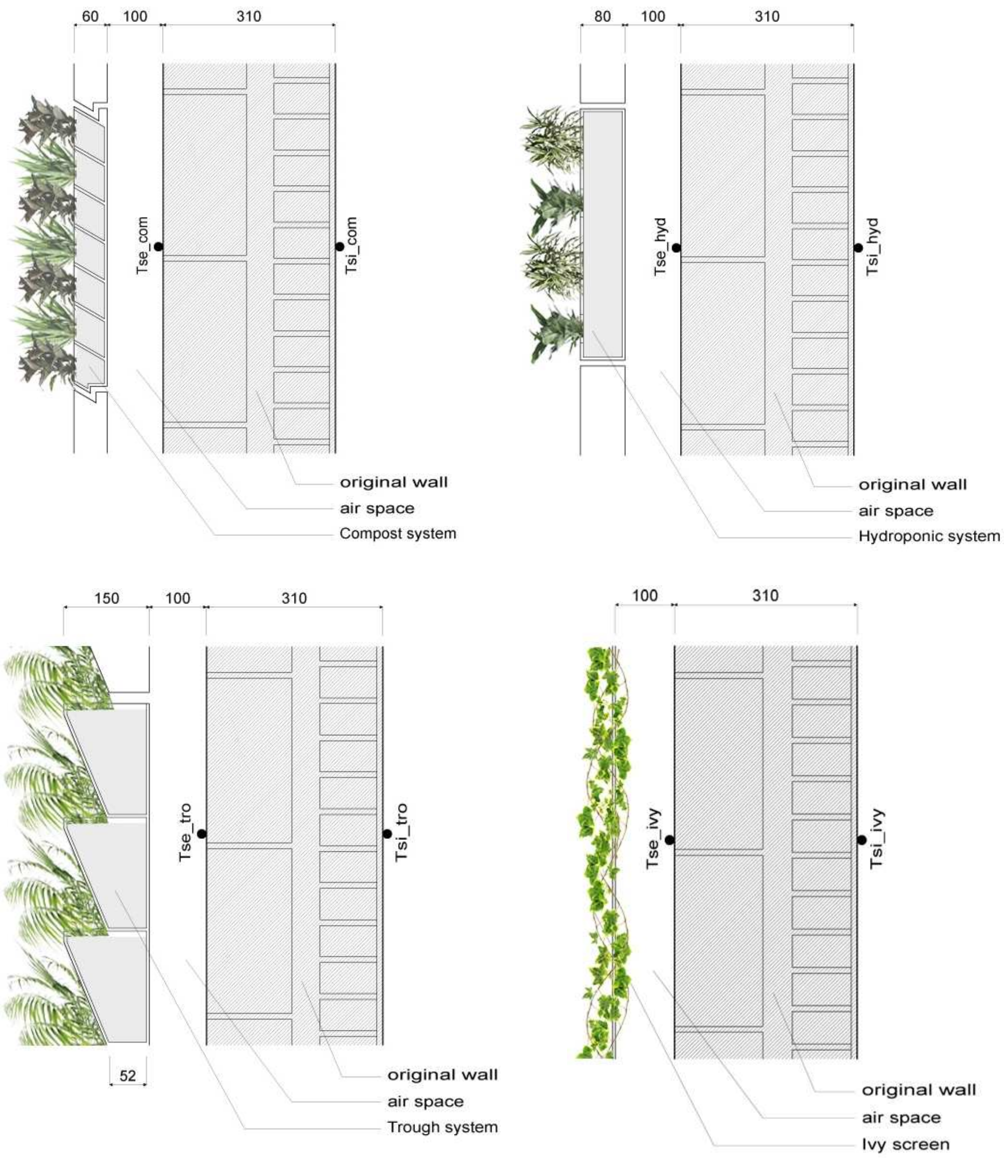


Figure 5.15 Sectional drawings of four tested green wall systems

Figure 5.16 shows the locations where temperature measurements of external and internal wall surfaces were taken for each divided section of respective green wall systems and a reference wall above them.

Thermocouples were located in the centre of each section of the green wall test beds. For the external surface temperatures, two measurements were taken approximately ten centimetres apart at the same height. This was to validate each section's measurements and also in case any faults occurred in one of the sensors. External temperature measurements were also taken on the surface of a reference wall which was the classroom directly above the green wall test beds for comparative analysis.

On the internal surface of the wall, thermocouples were installed in corresponding positions to their external counterparts behind the green walls. In the second floor classroom, internal wall surface temperatures were measured in the centre of the reference wall at three different heights. The heights of these measured points corresponded with the locations where three thermocouples were placed in line on the first floor wall for measurements of three variations of each system.

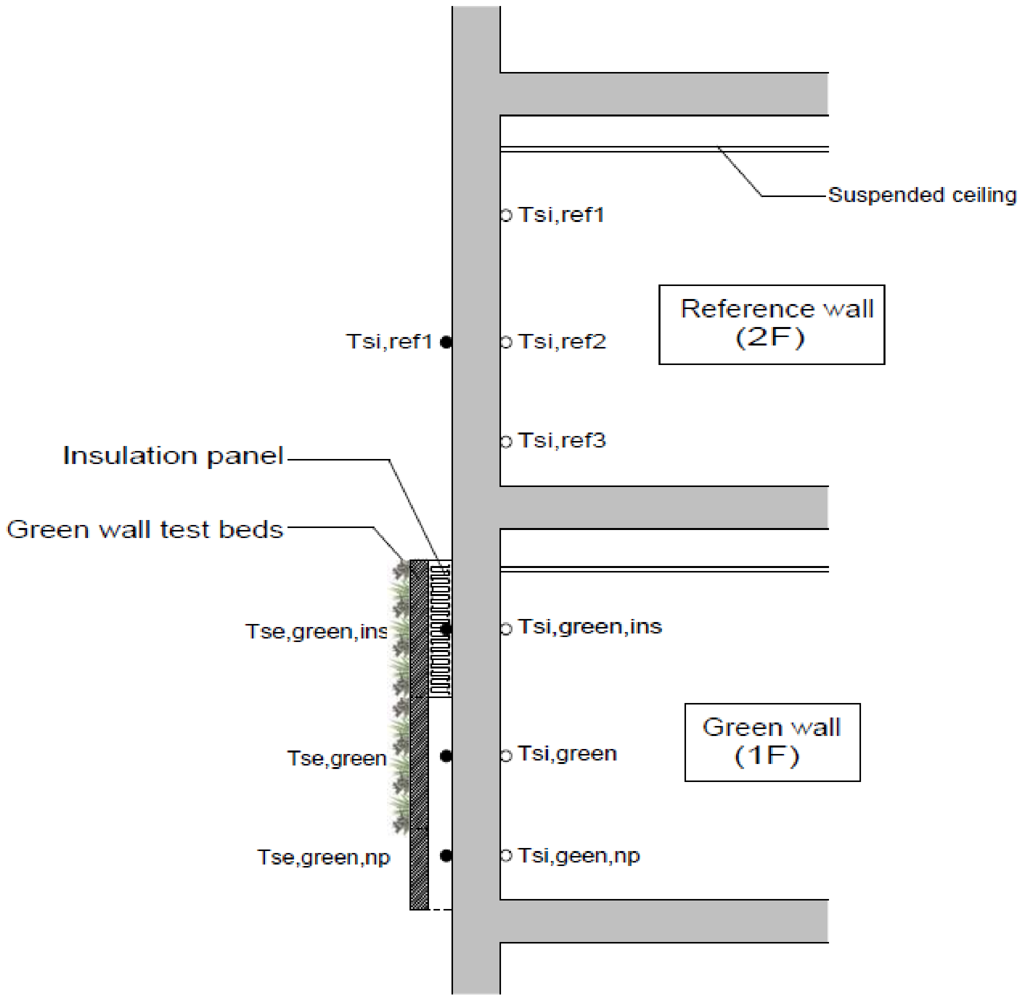


Figure 5.16 Sectional drawings of monitored walls showing the locations of internal wall temperature measurements in relation to the external measurements

Figure 5.17 Internal view of the observed wall with green wall test beds (first floor). The ends of internal thermocouples were covered by Kapton (thermal insulating) tape in order to minimise the influence of the indoor ambient air temperature.

Indoor air temperatures were measured in both classrooms on the first and second floors. A logger was attached to the external wall on which the green wall test beds were installed outside, and the other was placed in the centre of the internal wall where there would be no influence from direct sunlight through glazing (Figure 5.18). A logger was also attached to the centre of the ceiling (marked as 'Heating' in the plan) which recorded air temperature near the ceiling as well as the temperatures directly above three of five heating devices in the classroom on the first floor in order to monitor the heating schedule in the building. Identical indoor measurements were taken from the second floor class room for comparative analysis.

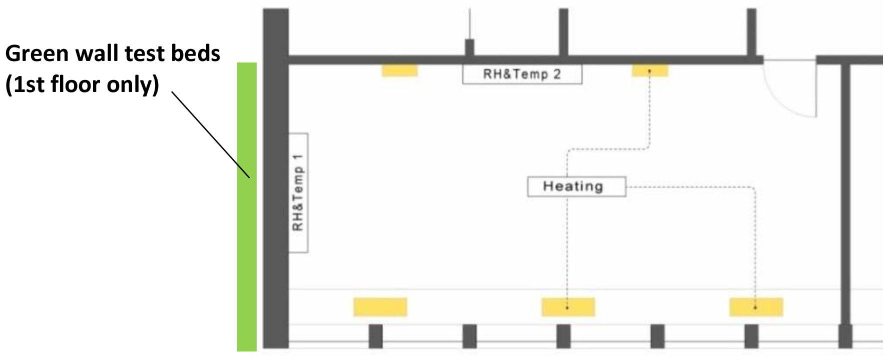


Figure 5.18 Plan of the first floor classroom and the location of indoor temperature measurements. Heating devices are highlighted in yellow

Table 5.5 List of equipment used for the study

Measurements	Equipment	Product
Surface and vegetation temperature	Type T Epoxy Coated Tip Thermocouple	5TC-PVC-T-24-180 (OMEGA)
Temperature logging	1ch Thermocouple Logger	OM-CP-TC101A (OMEGA)
	8ch Thermocouple Logger	OM-CP-OCTTEMP-A (OMEGA)
Heating monitoring	Four Channel Temperature Data Logger	OM-DVT4 (OMEGA)
Indoor temperature & relative humidity	Indoor Temperature and RH Logger	OM-CP-RHTEMP101A (OMEGA)
		U12-012 (HOBO)
Occupancy	Single beam people counter	Q-Scan UniComm V2.0 (Axiomatic Technology)

5.2.6. Weather data

Weather data used for analysis was collected from a weather station in an urban area of Sheffield, three kilometres away from the monitored building. A weather station was initially planned to be set up on the ground floor roof next to the classroom with green wall test beds. However, this did not materialise within the time constraints of the study. Among all available weather data in Sheffield during the twelve month study period, the data published on Sheffield Weather Page (2014) provided the most comprehensive and consistent data covering the period of the study within close proximity. The information included temperature, humidity, precipitation, solar radiation and wind speed at five minute intervals.

Historical average and recorded weather data for Sheffield

The city of Sheffield has a maritime temperate climate with mild weather influenced by the Gulf Stream much like the rest of the UK. Rain falls throughout the year with an average annual rainfall of 835mm and October to January are usually slightly wetter compared to the warmer seasons. The coldest months are December, January and February with a daily maximum average temperature of around 7℃ and a minimum temperature of 1.9℃. In July and August, which are the warmest months, the maximum temperature usually averages between 20.6–21.1℃ and the minimum between 12.4–12.7℃ (Met Office 2014).

In 2012, although the UK experienced the coolest autumn in twenty years, temperatures in December were close to average. There was a prolonged winter in the first four months of 2013, with an extremely cold March, the second coldest since records began including unseasonable snowfalls in April. In contrast to this, summer was warmer and sunnier than average, and a heat wave in July lasted almost the entire month resulting in the third warmest July on record. Temperatures in August and early autumn were very near to the average expected.

Total rainfall in December 2012 was well above average and in October 2013, heavy rain spread across the UK from various Atlantic storms. Sheffield received almost twice the normal rainfall for these months. In central England where Sheffield is located, April 2013 was comparatively dry although the precipitation rate quickly recovered and May recorded higher than average rainfall.

Total hours of sunshine in the UK were around the average at 98% of the historic average (1445 hours) in 2012, and 104% in 2013 except July which was the third sunniest since 1929 (Met Office, 2014) .

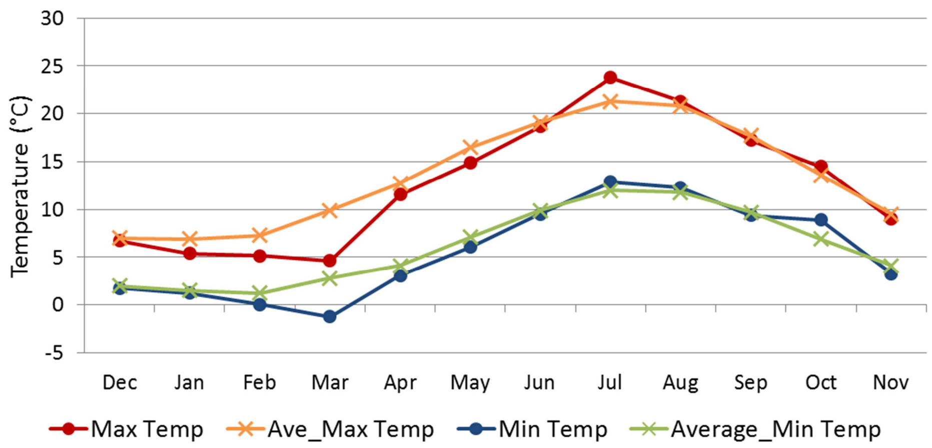


Figure 5.19 Comparison of monthly average maximum and minimum temperatures of the 12 month monitoring period compared to the historic average figures based on records from 1981 to 2010 (Source: Met Office 2014)

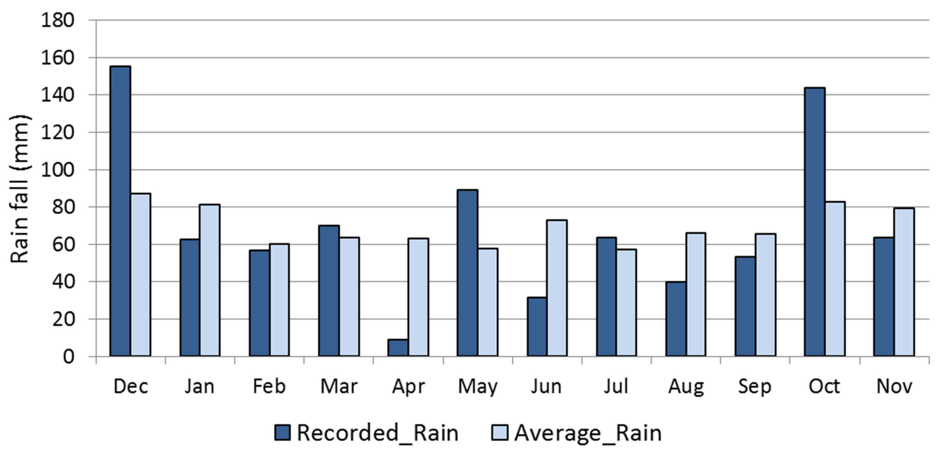


Figure 5.20 Comparison of monthly total precipitation of the 12 month monitoring period compared to the historic average

5.3. Results of thermal observation

Analysis was carried out on thermal data collected over a twelve month period between December 2012 and November 2013, and all statistical data analysis in this section was performed using Microsoft Excel.

A small amount of data measurements are missing from the twelve month monitoring period due to unforeseen circumstances beyond our control including power failure and misplaced equipment. The absent measurements were substituted with available data from alternative sources for the purposes of analysis.

Table 5.6 Missing measurements and substituted data.

Missing data	Period	Substituted by
All data	26-30th November	Data from 21-25th November
Internal wall surface temperature	10-17th September	Data from 6-9th,18-21th September
External wall surface temperature (Ivy screen)	19th June – 16th July	No comparative data available

5.3.1. External wall surface temperature

External wall surface temperatures at each location were measured using a pair of thermocouples for accuracy and validation of each other's measurements. A set of recorded measurements from the thermocouples were then cross checked side by side and analysis was carried out using averages of the two measurements.

Reduction of temperature fluctuation

Green walls reduced temperature fluctuations observed on the external surface of the reference wall throughout the year. In July, the warmest and brightest month, the daily temperature variation on the reference wall surface was 18℃ due to overheating occurred during the day, whilst green wall systems reduced this by 14.2–14.8℃ (Figure 5.21). These values became much smaller in winter; the daily temperature fluctuation of reference wall surface was 5.6℃ in January and green walls reduced this by 3.8–4.2℃ (Figure 5.22). The average daily temperature fluctuations of the wall surface behind the green walls were within 3.8℃ for all twelve months.

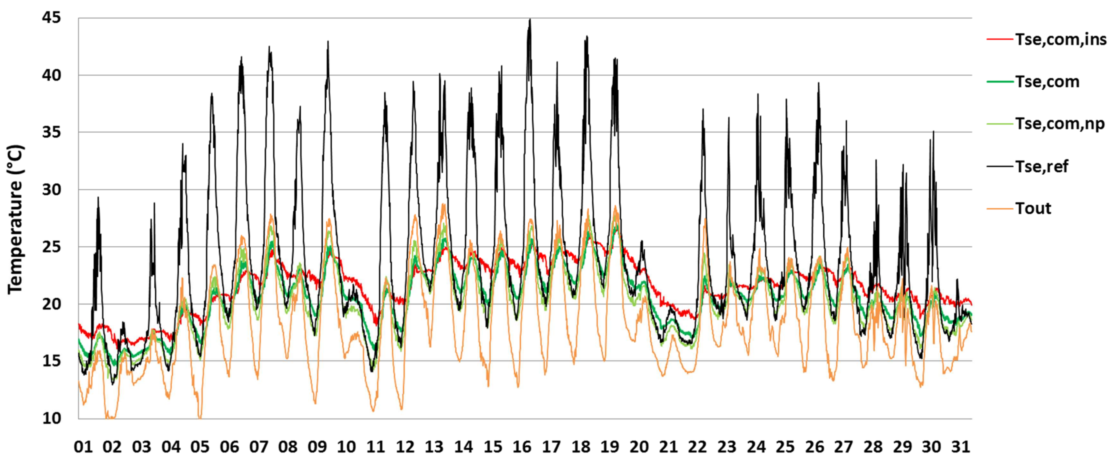


Figure 5.21 Recorded external wall surface temperature in July

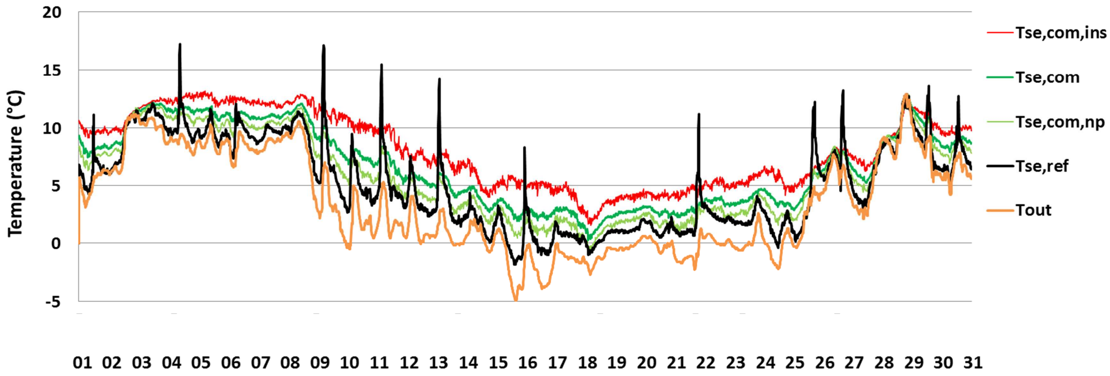


Figure 5.22 Recorded external wall surface temperature in January

Vegetation systems regulated the external surface temperature in both warm and cold weather conditions by moderating the influence of weather.

Figure 5.23 shows that on bright days in summer, the surface temperature of the reference wall spiked in the afternoon reaching a height of 44.9℃ after receiving high levels of solar radiation. Green wall cover stabilised the wall surface temperature behind the vegetation by reducing heat reaching the buildings surface. Plants kept air temperature within the foliage approximately 4℃ lower than the outdoor air temperature during the day by providing shading and evapotranspirative cooling effects. However at night, the air temperature inside the foliage was increased by approximately 3℃. The temperature inside the substrate was more sensitive to the influence of outdoor climatic conditions, thus, '$T_{sub,com}$' graph shows a similar profile to the outdoor air temperature. This indicated that although foliage lowered the air temperature inside, the substrate of the living wall system was influenced by radiant heat travelling through the foliage layer. That said, the large amount of radiant heat would not reach the wall surface behind the system as it would be released back into the air as latent heat from evaporating water contained within the substrate.

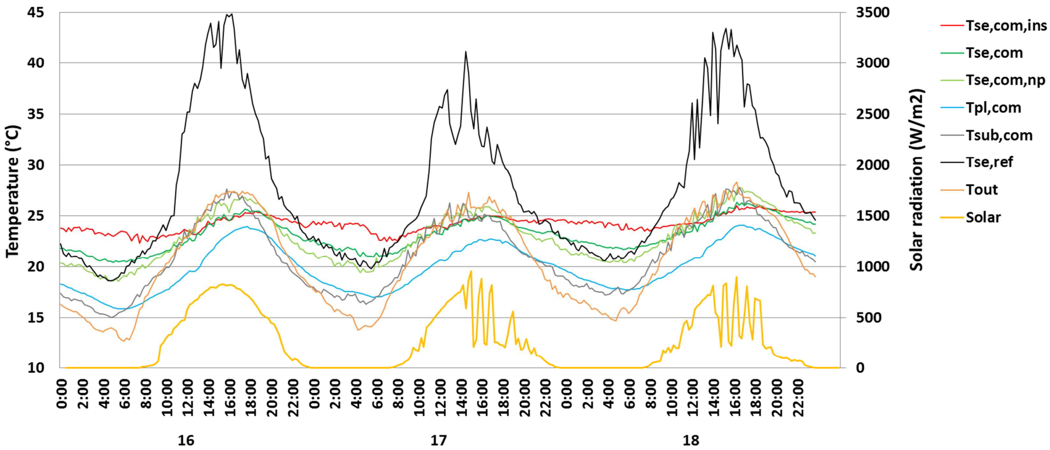


Figure 5.23 Recorded temperatures for the Compost system between 16th and 18th July (External surface & temperature within the system)

Green walls also reduced the influence of the outdoor climate in winter by providing insulating effects. They kept the wall surface temperature higher than the reference wall for the majority of the time as demonstrated in Figure 5.24. The surface temperature of the reference wall followed the profile of outdoor air temperature and also spiked briefly around midday on some bright days. Vegetation showed greater insulating effects during the night as the exposed surface temperature of the reference wall dropped in line with the decreasing ambient temperature.

Similar to the summer results, the temperature inside the substrate fluctuated more than the air inside the foliage, possibly due to the moisture content within the substrate which may have lowered the temperature by evaporative cooling. Despite the temperature inside the substrate, the results showed the thermal resistance of the living walls provided constant insulating benefits and stabilised the external wall surface temperature behind the system during cold weather.

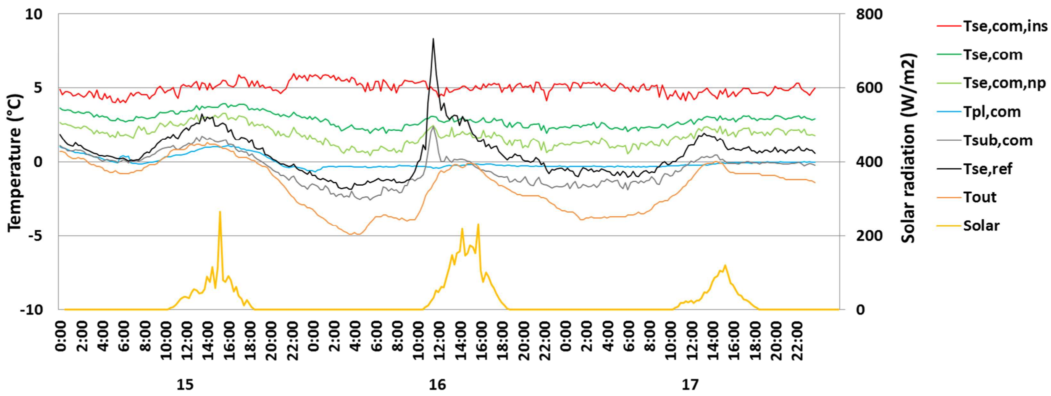


Figure 5.24 Recorded temperatures for the Compost system between 15th and 17th January (External surface & temperature within the system)

The effect of green walls to regulate temperature in varying seasonal weather was also apparent in the daily temperature profiles.

During the spring and summer months (April–September), the wall surface temperature behind the green walls stayed cooler than the reference wall the majority of the day (Figure 5.25). The average total daily solar radiation exceeded 10kW/m^2 during this period; the external surface temperature of the reference wall rose sharply between 10:00–12:00 and reached a peak at around 15:00. It quickly descended after sunset due to the influence of cooler ambient air until reaching its lowest figure at around 4:00. The wall surface behind the green walls stayed cooler than the reference wall on average for thirteen hours a day in May and sixteen hours in July.

Monthly averages of surface temperature fluctuation for the reference wall were 14.2–18℃ in spring and summer whilst the gree n walls reduced this to 2.5–3.6℃. The reductions of diurnal temperature variation were more substantial in warmer and brighter months.

The temperature behind the systems with an added insulation panel did not largely fluctuate throughout a summer day, and it became warmer than the reference wall during the night by insulating the wall. The systems without plants had less insulating effects and kept the wall surface behind the vegetation cooler than the reference wall most of the time in summer. Between 12:00 and 18:00, the temperature difference among three variations of green wall systems became less noticeable.

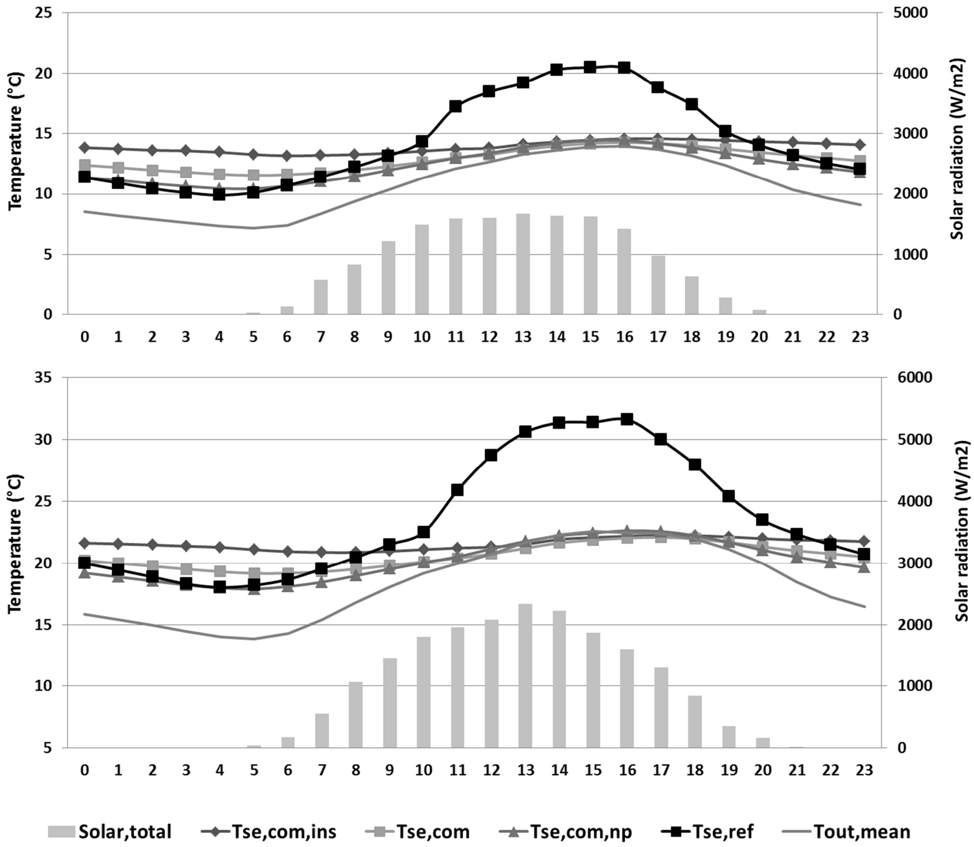


Figure 5.25 Hourly mean temperature of the external wall surface over the months of April (top) and July (bottom)

In contrast to the warmer seasons, the wall surface temperature behind the green walls stayed warmer than the reference wall the majority of the day during autumn and winter (October–March) (Figure 5.26). January was the second darkest month with a total average daily solar radiation of 1.7kW/m^2 which was 9% of the figure for the brightest month in summer. Since there was little sunlight to warm the exposed wall surface, the wall behind the vegetation systems stayed warmer compared to the reference wall all day except for two hours at midday.

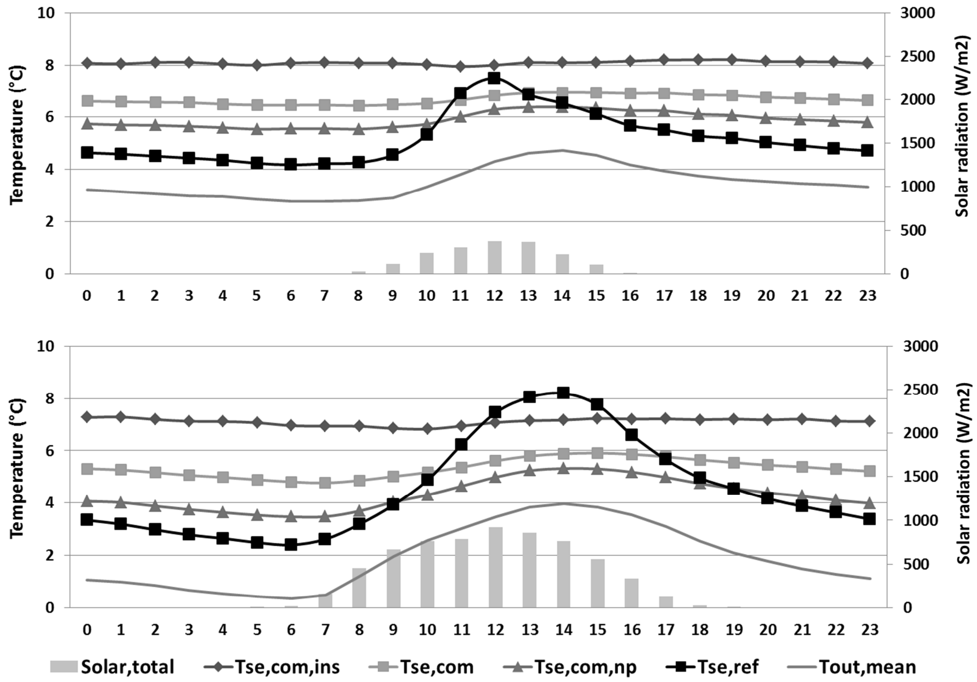


Figure 5.26 Hourly mean temperature of the external wall surface over the months of January (top) and March (bottom)

The coldest month during the observation period was March with a daily average temperature of 1.9℃; however, it was brighter than January receiving three times the level of solar radiation. This increased the temperature of the reference wall, and on average its surface stayed warmer than the wall behind the green walls for six hours during the day in March. The reference wall warmed by solar radiation in the afternoon quickly cooled in the evening and the temperature fell to its lowest figure between 5:00–6:00, resulting in an average diurnal temperature fluctuation of 5.6℃ for January and 9.1℃ for March. The wall surface temperature behind the green walls stayed within a range of 1.7℃ and 2℃ for those respective months. Both increases in external surface temperature and reductions in the daily temperature fluctuations were more significant in the case of the green walls with an added insulation layer and the lack of plants slightly decreased the impact compared to the original systems.

Impacts on the daily peak and minimum temperature

As described above, green wall systems minimised the daily temperature fluctuation experienced on the reference wall surface by reducing daytime and increasing night-time temperatures. Figure 5.27 demonstrates this general trend observed throughout the year. In this section, the cooling and insulating effects of vegetation systems over the twelve months were quantified by analysing the differences in daily peak and minimum temperatures.

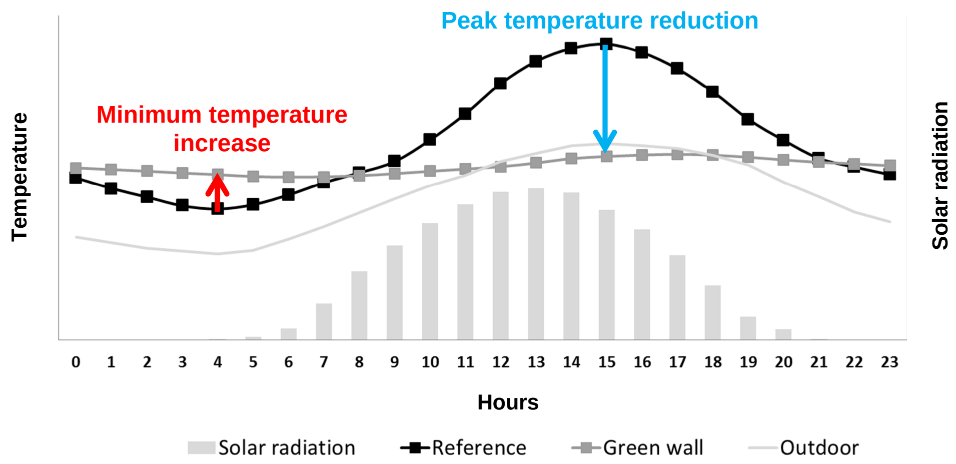


Figure 5.27 Schematic diagram showing basic patterns of daily temperature variations of the external surface for the reference wall and the wall behind the green wall systems

All four tested green walls reduced the monthly average daily peak temperatures and increased daily minimum temperatures throughout the year regardless of season.

Average peak surface temperatures of the green walls were similar to outdoor air, and the reduction was more significant in summer compared to the colder months, further highlighting the effectiveness of vegetation systems in minimising the influence of solar radiation (Figure 5.28).

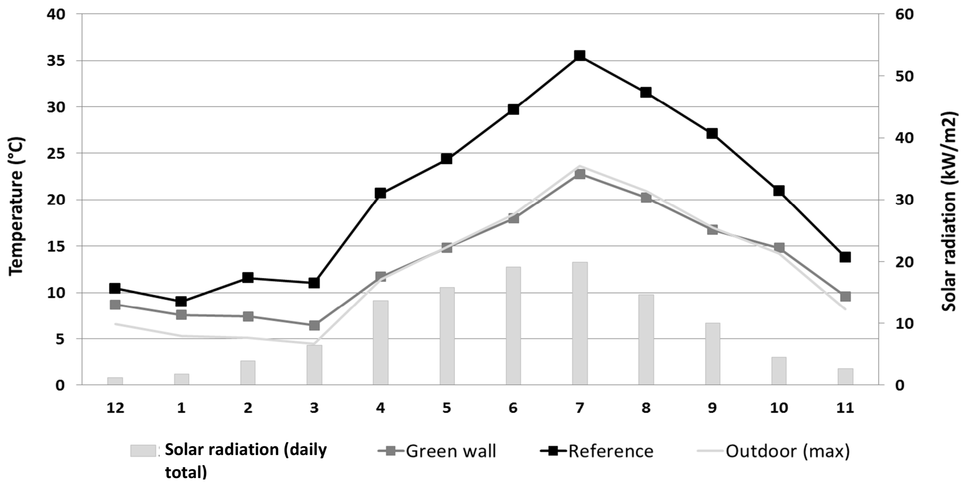


Figure 5.28 Monthly average daily peak temperatures of the external wall surface for the reference wall and the average of the four green wall systems

The highest temperature recorded on the reference wall surface was 44.9℃ on the day when the maximum outdoor temperat ure was 27.4℃ and the total solar radiation was 29kW/m^2. Peak surface temperatures behind the green walls on the same day were significantly lower at 26.7–27℃ with a reduction of 17.9–18.2℃. An average pe ak surface temperature for July on the reference wall was 35.5℃ when the green walls reduced this to 22.5–23.3℃ (a reduction of 1 1.3–12.9℃).

The green walls also slightly decreased the peak surface temperature in the colder months. Between December and February, the average peak temperature of the reference wall was 9–11.6℃ and vegetation cover reduced it by 1.5–4.2℃. This could be a negative i mpact of green walls as the cooler outer wall surface increases heat transferred from the warmer internal space through the wall in winter.

As for the daily minimum temperatures which were recorded in the early hours of the morning, monthly averages for the green walls were higher than the reference wall in all twelve months of the year. In the colder months (November–March) when the average minimum outdoor temperature was below 5℃, the green walls increased the wall surface temperature by 2.4–3.1℃. This figure was slightly lower for the rest of the year and between 1.7–2.2℃ (Figure 5.29).

The lowest temperature recorded on the reference wall surface was -2.3℃ on a day when the minimum outdoor temperature was -3.9℃ although the temperature behind green walls was 0.3℃. The external surface temperature behind the vegetation never fell below zero.

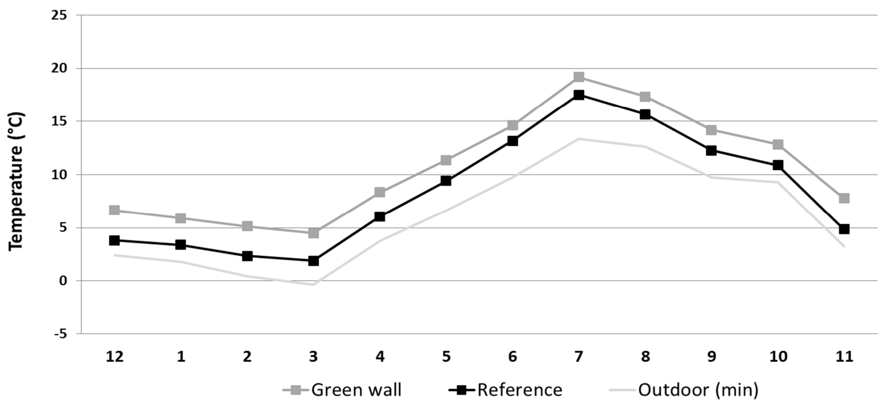


Figure 5.29 Monthly average daily minimum temperatures of the external wall surface for the reference wall and the average of four green wall systems

System comparison

There was no significant difference impacting on the external surface temperatures among the four tested systems as shown in Table 5.7.

With regards to the peak surface temperature reductions, the difference in value across all systems except for Ivy screen was within 0.2℃. Although the wall behind the Ivy screen was on average 0.6℃ warmer than the others at its peak during the spring and summer months, this could be a result of data lost during parts of June and July rather than actual inferior performance of the system (see Table 5.6). In fact, the system demonstrated the same effects as the others in reducing peak temperatures in the colder months.

The difference between systems was also marginal for the increase in daily minimum surface temperatures. In general, increases due to Compost and Ivy systems were comparable in all seasons, and Hydroponic showed a slightly higher figure (+0.2℃) and Trough showed a further improvement in performance in increasing the minimum temperature (+0.6℃) compared to the other two, possibly due to an increased thermal resistance of 150mm substrate layer providing better insulating effects.

Table 5.7 Differences in external surface temperatures between the reference wall and four tested green wall systems (Reference – Green wall) in different seasons* (℃)

		Compost	Hydroponic	Trough	Ivy
Spring & Summer	Peak temp.	-10.9	-10.9	-10.9	-10.3
	Minimum temp.	+1.6	+1.8	+2.2	+1.6
Autumn & Winter	Peak temp.	-3.8	-3.7	-3.6	-3.8
	Minimum temp.	+2.5	+2.7	+3.0	+2.3

* Spring and summer: April-September and autumn and winter: October-March

The influence of added insulation and the absence of plants on the performance of green wall systems was more apparent by way of minimum temperature increases compared to maximum temperature reductions (Table 5.8).

The systems with an added insulation layer increased the minimum wall surface temperature during the autumn and winter months by an average of 1.3℃ compared to the original green wall systems. A lack of plants on the other hand, reduced the insulating performance of the original systems and decreased the average minimum surface temperature by 1.5℃ in all four seasons. Adding insulation also minimised the undesirable effect of green walls to reduce peak surface temperature during the cold months by providing insulation during the day as well as the night, increasing the average peak temperature by 1.2℃ compared to the original systems.

However, the increases in surface temperature influenced by added insulation could potentially provide negative effects in warmer climates than the UK as this layer also increased the daily minimum temperature during the spring and summer months by 1.3℃. The impacts of insulation and plants on peak temperature reductions during the warmer months was minimal as all three variations reduced the peak temperature by over 10℃ and the difference in reduction rates became marginal.

Table 5.8 Differences in external surface temperatures between the reference wall and each variation of green wall systems (Reference – Green wall) in different seasons* (℃)

		Green wall (+insulation)	Green wall	Green wall (no plants)
Spring & Summer	Peak temp.	-10.4	-10.8	-10.1
	Minimum temp.	+3.1	+1.8	+0.3
Autumn & Winter	Peak temp.	-2.5	-3.7	-4.1
	Minimum temp.	+4.0	+2.6	+1.1

*Values are averages of the four tested green wall systems for each variation. Spring and summer: April-September and autumn and winter: October-March

5.3.2. The influence of weather conditions on the external wall surface temperatures

To investigate how weather influenced the performance of vegetation systems, correlations of weather data against the impact of green walls on external wall surface temperature were analysed here.

Table 5.9 Pearson's coefficient values (*r*)* for correlations between each weather element and the wall surface temperature differences (Reference - Compost) for each month

	Outdoor temp.	Solar radiation	Wind speed	Rainfall
DEC	-0.498	-0.536	-0.357	-0.010
JAN	-0.338	-0.617	-0.294	-0.118
FEB	-0.625	-0.795	-0.083	0.032
MAR	-0.456	-0.675	-0.189	0.004
APR	-0.497	-0.765	-0.197	0.017
MAY	-0.722	-0.730	-0.006	0.097
JUN	-0.724	-0.739	-0.188	0.073
JUL	-0.778	-0.757	-0.100	0.044
AUG	-0.716	-0.701	-0.124	0.070
SEP	-0.665	-0.777	-0.113	0.025
OCT	-0.509	-0.764	0.051	0.060
NOV	-0.440	-0.725	-0.212	0.030

* The degree of correlation based on Pearson's correlation coefficient values (*r*) are categorised here as: ▭ high to perfect (±0.7-1.0), ▭ medium (±0.4-0.7), ▭ low (±0.2-0.4) and ▭ very low to no correlation (0.0-±0.2).

As Table 5.9 illustrates, the highest degree of correlation was observed between green wall performance and the solar radiation level among the four weather elements studied here. The higher the solar radiation, the cooler the external wall surface behind the green walls became compared to the reference wall in all seasons. This correlation was stronger in months experiencing higher solar radiation exposure. July was the brightest month during the monitored period with total solar radiation of 19.9kW/m^2 and this resulted in the highest degree of correlation. In less brighter months, correlation coefficient values slightly decreased as overheating on the reference wall was less significant (Figure 5.30).

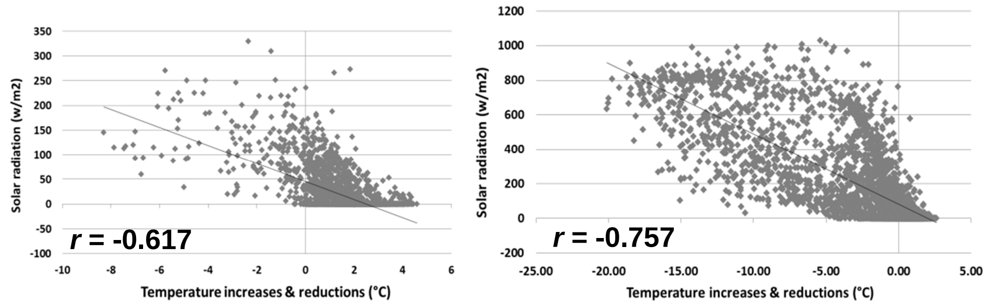


Figure 5.30 Correlation of solar radiation against the differences in external wall surface temperatures (Reference-Compost) in January (left) and July (right)

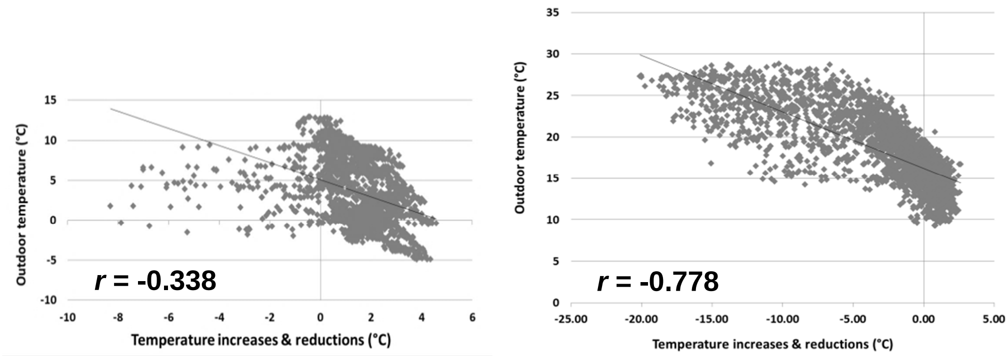


Figure 5.31 Correlation of outdoor air temperatures against the differences in external wall surface temperatures (Reference-Compost) in January (left) and July (right)

Relatively high correlation was also found against the outdoor air temperature throughout the year and it was particularly strong during the warmer months between May and August. In general, for each degree increase in the outdoor air temperature, the value of temperature differences between the reference wall and green wall lowered by 0.7–1.0℃ (Figure 5.31).

There was very little influence from wind speed on the surface temperature differences observed in spring and summer. However, the results for November, December and January showed clearer correlation in which the value of temperature differences decreased as the value of wind speed increased. The result was not associated with the level of wind speed as November was the second calmest month with a daily average wind speed of 5.6mph with May being the windiest at 9.8mph. This result suggests that wind may actually reduce the performance of green walls in colder weather (Figure 5.32).

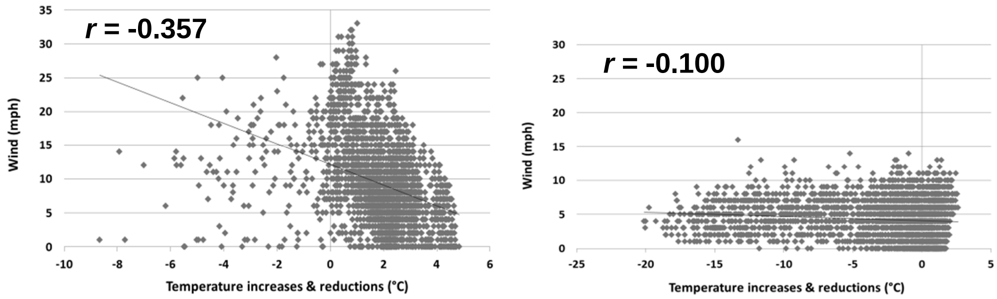


Figure 5.32 Correlation of wind speed against the differences in wall surface temperatures (Reference-Compost) in December (left) and July (right)

No noticeable correlation was observed against rain fall in all four seasons. This could be due to the fact that a large proportion of rain falling on foliage of the green walls ran off the leaves without being collected by the vertical substrate layer. Thus, the moisture level of growing medium, which could be an influential factor in the thermal performance of green walls, was largely dependent on irrigation rate rather than rain fall.

5.3.3. Internal wall temperature

The internal wall surface temperature behind the green walls was measured at three different heights in corresponding positions to where measurements were taken on the exterior wall surface. In the second floor classroom, wall surface temperatures were measured in the centre of the reference wall at three separate heights. These measured points corresponded with the locations of three thermocouples placed in line on the first floor wall for measurements of the three variations of each green wall system (See Figure 5.16).

Analysis of the impacts on internal surface temperatures in this section was carried out by comparing the data from the respective green wall sections against the corresponding measurements from the reference wall. The corresponding measurements and the heights on the wall where internal surface temperatures were measured were as follows.

$T_{si,green,ins}$:$T_{si,ref1}$ (Floor level +0.4m)

$T_{si,green}$:$T_{si,ref2}$ (Floor level +1.1m)

$T_{si,green,np}$:$T_{si,ref3}$ (Floor level +1.8m)

In order to reduce the effects of occupancy and mechanical heating during the winter period, analysis of internal surface temperatures was carried out using data collected during weekends and holidays only when the recorded daily occupancy of both rooms was less than ten and the observed rooms were both unheated.

Impacts on the overall surface temperature

Green walls mounted on the exterior of the monitored wall reduced the temperature fluctuation of the internal wall surface when the range of outdoor temperature shifted over a period of a few days. In general, the interior surface temperature of the wall with vegetation stayed cooler than the reference wall when the outdoor air temperature was higher, and warmer when the surface temperature of the reference wall decreased along with the outdoor air. This trend was particularly evident in the measurements from seasons with varying weather, such as spring and autumn, and is well demonstrated in Figure 5.33.

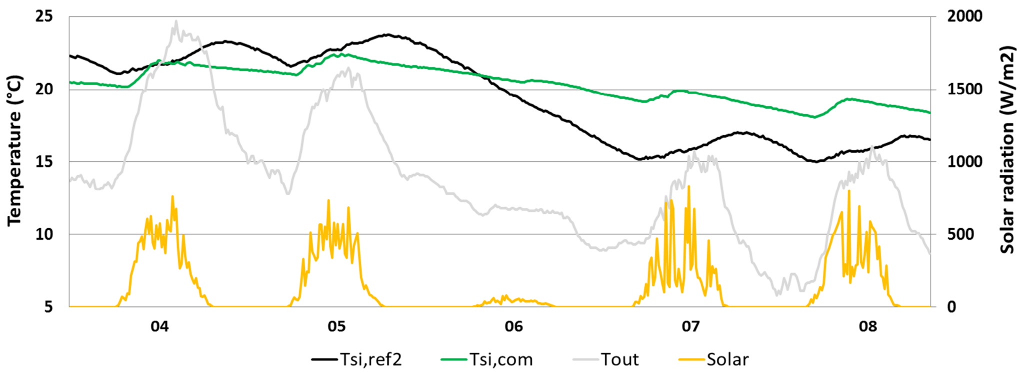


Figure 5.33 Recorded internal wall surface temperatures behind the compost systems and corresponding measurements from the reference wall (4th – 8th September)

The green walls decreased the overall temperature of the internal wall surface in spring and summer (April-September) and increased it in autumn and winter (October-March) in comparison to the reference wall. As a result, they reduced the daily peak and minimum surface temperatures in warmer weather and increased both temperatures in cooler weather (Figure 5.34 and Figure 5.35).

In summer, the internal surface temperature of the reference wall increased in the evening and peaked around midnight whilst both indoor air and internal wall surface temperatures behind the green walls peaked at noon. This suggests that solar radiation heat transmitted through the exposed surface during the day was retained and transferred through the wall structure, increasing the internal surface temperature of the reference wall at night.

Contrary to this, the internal wall surface temperature behind the green cover did not show the influence of outdoor weather and there were no temperature increases observed during the night. Both the indoor air and internal wall surface behind the green walls reached a daily temperature low at around 5:00–6:00 whilst minimum temperatures of the reference wall surface were recorded at around 13:00.

Since minimum and maximum temperatures were recorded at different hours of the day on the two walls, night time temperature reductions became more significant than day time temperatures. However, as the overall temperature of the reference wall surface was increased by the influence of stored solar radiation within the structure, the internal wall surface behind the vegetation constantly stayed cooler throughout the day, by an average of 1.7℃ in July (Figure 5.34).

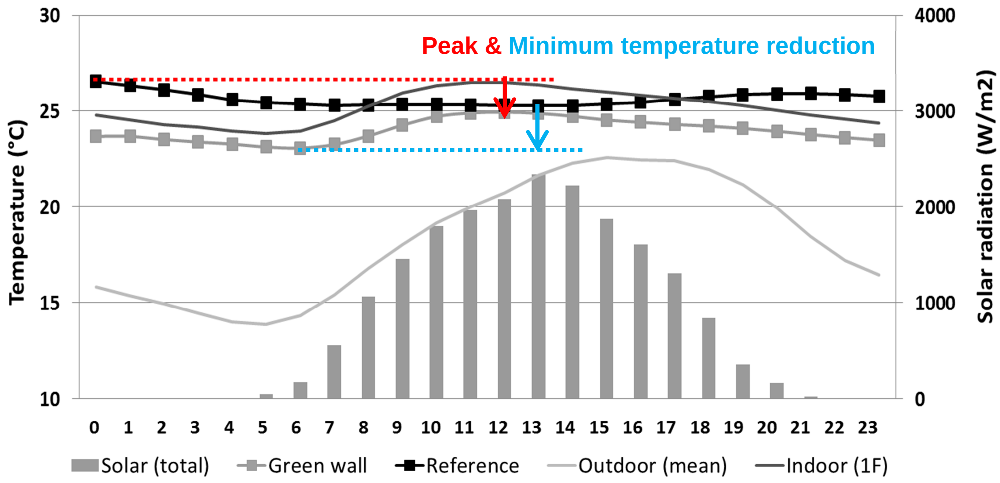


Figure 5.34 Hourly mean temperature of internal wall surface over the month of July for the reference wall and an average of the four green wall systems

In contrast to the results of summer, temperatures behind the vegetation remained higher than the reference wall throughout the day in colder seasons, increasing the internal wall surface temperature by 2.1℃ on average for January. As daily variations of the outdoor air temperature were small and the solar radiation rates low during winter, internal surface temperatures did not largely fluctuate on either of the monitored walls. Although temperature variations within a day were minimal, a delay in temperature peak on the reference wall similar to the summer result was also observed in the colder months where the reference surface peaked at around 20:00, eight hours after the peak of indoor air and wall surface temperatures behind the green wall systems (Figure 5.35).

The increase in external surface temperature in winter appeared to have resulted in warmer internal wall surface. Although the reference wall that received solar radiation during the day slightly increased the internal surface temperature in the evening, the surface behind green walls constantly stayed approximately 2℃ warmer througho ut the day during the winter months.

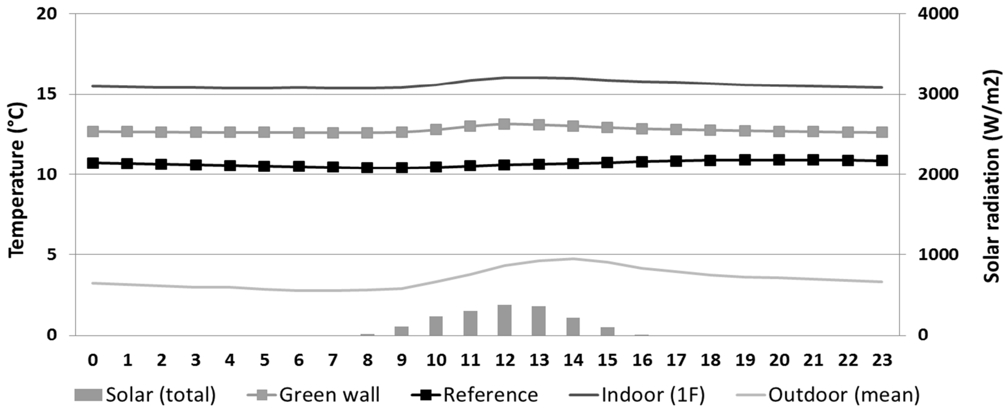


Figure 5.35 Hourly mean temperature of the internal wall surface for the month of January for the reference wall and an average of the four green wall systems

Impacts on daily peak and minimum temperature

As previously explained, green wall systems decreased both daily peak and minimum temperatures of the internal wall surface during the spring and summer months and increased both during the colder months. In this section, the differences in recorded daily peak and minimum temperatures between the reference wall and the green walls are analysed in order to quantify the effects of vegetation cover on the thermal conditions of the interior wall surface over twelve months.

In Figure 5.36 and Figure 5.37, both graphs of average daily maximum and minimum temperatures show similar profiles, indicating higher surface temperatures on the reference wall between May and August and lower surface temperatures between November and March compared to the surfaces with green walls. Differences between the two values become insignificant in the spring and autumn months.

During summer (June & August), green wall systems reduced daily peak temperatures of the internal wall surface by 1.5℃ on average and daily minimum temperatures by 1.3℃; during winter (Decem ber–February), they increased the daily peak temperatures by 1.7℃ and the minimum temperature by 2.1℃.

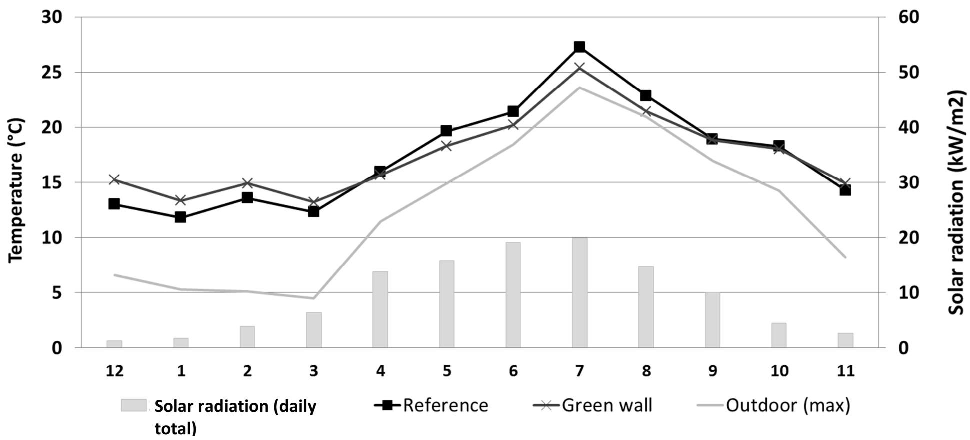


Figure 5.36 Monthly average of daily peak temperatures of the internal wall surface for the reference wall and an average of the four green wall systems

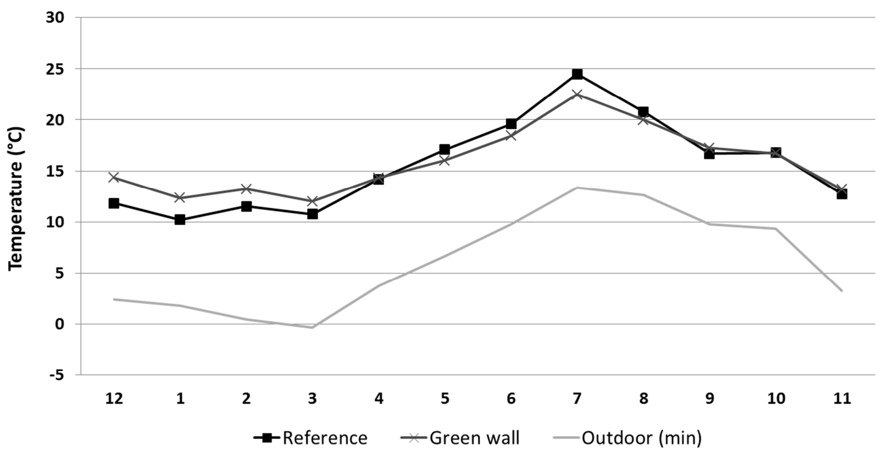


Figure 5.37 Monthly average of daily minimum temperatures of the internal wall surface for the reference wall and an average of the four green wall systems

System comparison

Differences in the impacts on internal surface temperatures between the four tested green wall systems were marginal, as they were on the external wall surface. Table 5.10 shows the temperature differences between the reference wall and each tested green wall; the variation among four systems were within 0.4℃. In general, a slightly cooler wall surface behind the Ivy screen compared to the other systems resulted in a 0.3℃ greater temperature reduction in the warmer m onths and less of a temperature increase in the colder months. The difference among the other systems was insignificant at around 0.2℃.

Table 5.10 Differences in internal surface temperatures between the reference wall and four tested green wall systems (Reference - Green wall) in different seasons* (℃)

		Compost	Hydroponic	Trough	Ivy
Spring & Summer	Peak temp.	-1.1	-1.0	-1.0	-1.1
	Minimum temp.	-0.5	-0.6	-0.4	-0.8
Autumn & Winter	Peak temp.	+1.3	+1.1	+1.3	+0.9
	Minimum temp.	+1.6	+1.4	+1.6	+1.2

* Spring and summer: April-September and autumn and winter: October-March

Adding insulation to green wall systems increased the overall temperature of the internal wall surface and removing plants decreased it when compared with original systems (Table 5.11).

Systems with an added insulation panel increased the minimum surface temperature during autumn and winter months by 0.7°C while a lack of plants decreased both peak and minimum temperatures compared to original systems. Potential negative effects of added insulation increasing surface temperature during the spring and summer months were observed on the internal measurements as well as external. The insulation panel increased both peak and minimum surface temperatures by 0.4℃ while the absence of plants decreased both compared with original systems.

Table 5.11 Differences in internal surface temperatures between the reference wall and each variation of green wall systems (Reference - Green wall) in different seasons* (℃)

		Green wall (+insulation)	Green wall	Green wall (no plants)
Spring & Summer	Peak temp.	-0.6	-1.0	-1.7
	Minimum temp.	-0.2	-0.6	-0.7
Autumn & Winter	Peak temp.	+1.3	+1.2	+0.6
	Minimum temp.	+2.0	+1.3	+1.1

*Values are averages of four tested green wall systems for each variation. Spring and summer: April-September and autumn and winter: October-March

5.3.4. Indoor air temperature

Indoor air temperatures were measured by two loggers: one attached on the monitored wall and the other mounted on the centre of the internal wall inside the two classrooms (See Figure 5.18). As it was in the case of internal surface temperature, data collected on days when either of the classrooms were occupied for teaching activities or mechanically heated were excluded from this analysis.

In spring and summer, room temperatures measured in the centre of the two classrooms both peaked around noon due to the influence of solar radiation through the other external wall facing southeast. Recorded indoor air temperatures near the wall behind the green wall testbeds showed similar temperature profiles to those measured in the centre of the room. However, air temperature near the reference wall was clearly affected by the warmer interior wall surface during the night and peaked much later at around midnight, similar to the internal wall surface temperature.

July 2013 was an exceptionally warm month for an average UK summer, and the classroom temperatures remained above the comfort range of the occupants at 23℃ (CIBSE 2008) for a large period o f time. Hourly mean temperatures inside the classroom with green walls were constantly lower than the reference room above at both measured locations over the month of July, although the reduction in temperatures was less evident in the centre of the classroom compared to the temperature near the observed wall. Green wall testbeds collectively reduced daily mean temperatures inside the classroom by 0.4℃ in the centre and 1.5 ℃ next to the wall in July (Figure 5.28).

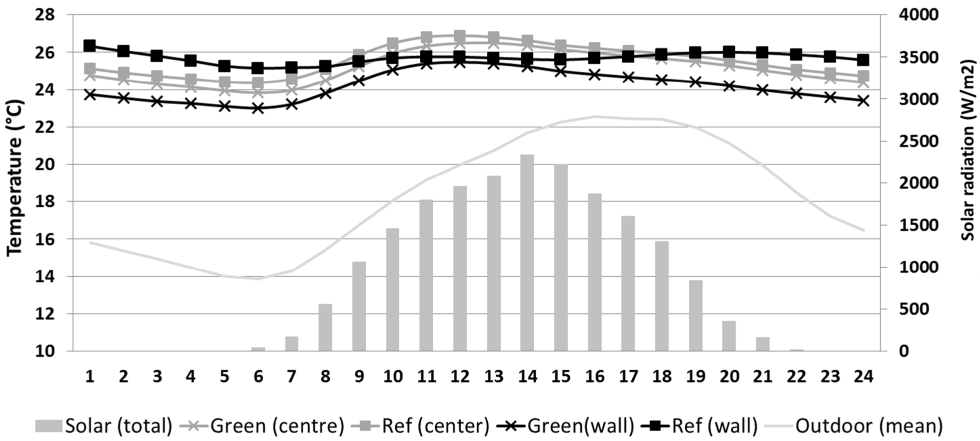


Figure 5.38 Hourly mean temperature of indoor air recorded near the monitored wall (wall) and in the centre of the classrooms (centre) over the month of July

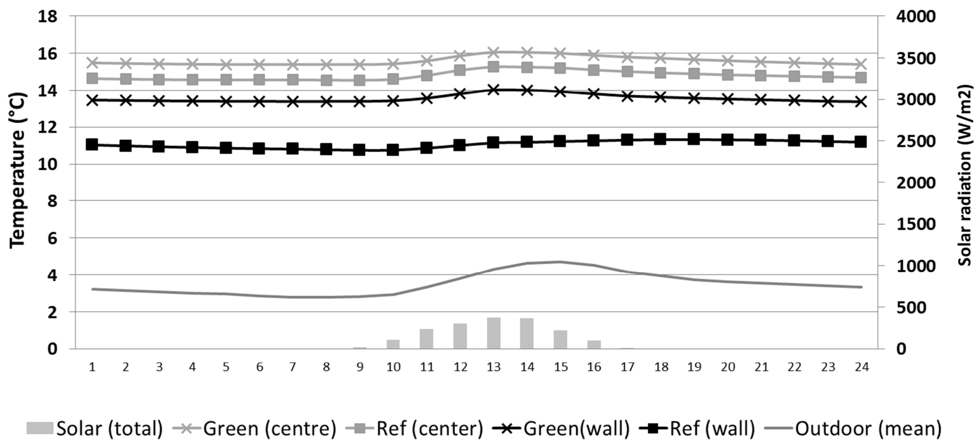


Figure 5.39 Hourly mean temperature of indoor air recorded near the monitored wall (wall) and in the centre of the classrooms (centre) over the month of January

In contrast to the results for summer, hourly average indoor air temperatures recorded in the classroom with green walls remained consistently warmer than its counterpart in the room above at both monitored locations. Figure 5.39 shows that air temperatures in the centre of both classrooms and near the wall behind the test beds peaked at noon while the temperature near the reference wall peaked at around 18:00, once more, reflecting the results of the internal wall surface measurements. As was observed in the warmer period of the year, the temperature differences were less significant in the centre of the classrooms. In January, green wall testbeds increased the daily mean temperature inside the classroom by 0.8℃ in the centre and 2.5℃ next to the wall.

Over the twelve month observation period, green wall test beds increased the indoor air temperature in most seasons apart from summer when they had a reverse effect. During the summer months (June & August), the classroom with green walls stayed 1℃ cooler near the wall and 0.5℃ cooler in the centre of the room compared to the reference room. In winter (December–March), the room with green walls stayed 2.3℃ warmer near the wall and 0.8℃ warmer in the centre of the room. Differences in the average air temperature inside the two classrooms became less significant in other seasons (Figure 5.40).

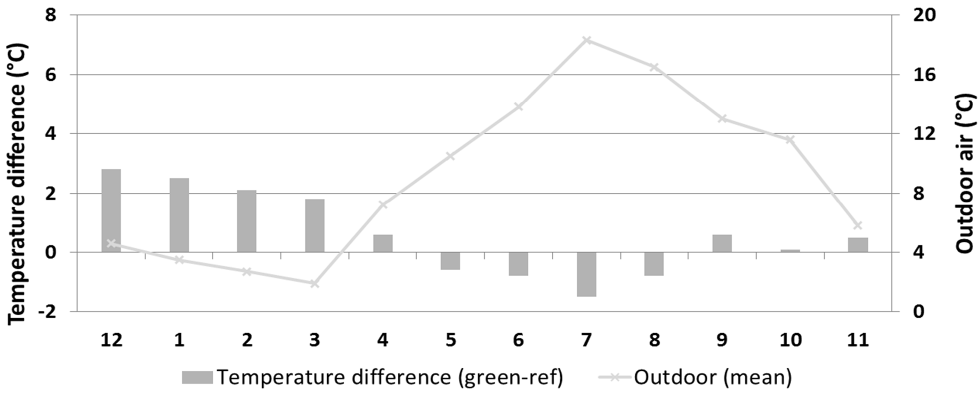


Figure 5.40 Difference in monthly mean indoor air temperatures near the monitored walls between the classroom with green walls and the reference room

5.4. Summary and discussion

Results of the temperature observations showed that the green walls reduced temperature fluctuations observed on the external surface of the reference wall throughout the year, and the impacts on external wall surface were reflected on the internal surface and air temperatures inside the observed rooms.

External wall surface temperatures

All four tested green walls regulated the wall surface temperature behind the systems and reduced the daily temperature fluctuations occurring on the reference wall throughout the year.

Green walls were particularly effective in reducing daytime temperatures in summer, decreasing the average daily peak temperature by 12.1℃ during the warmest and brightest month when the peak temperature of the reference wall surface averaged 35.5℃. The result was in line with the findings in subtropical climate that showed the peak temperature reduction of 11.5℃–16℃ for living walls (Chen et al. 2013; Cheng et al. 2010; Wong et al. 2010). Green walls also increased the daily minimum temperature of external wall surface in cold weather although the increase was much smaller compared to the peak temperature reductions in summer. They increased the monthly average daily minimum temperature by 2.8℃ between November and March when the mean m inimum outdoor temperature was below 5°. Similar insulating effect was observed on a green roof by Simmons et al. (2008), reporting 2–5°C higher roof membrane temperatures under the vegetation when minimum outdoor temperature was around 5℃ in Austin, Texas, USA.

The degree of green wall's impacts on the external wall surface temperature was strongly correlated to the solar radiation levels and outdoor air temperature throughout the year. The correlations were stronger in months experiencing higher solar radiation exposure and outdoor temperatures when the reference wall surface was overheating during the day. Jim and Peng (2012) also found solar radiation to be a key meteoroidal factor in determining the thermal effects of green roofs, stating the optimal benefits of vegetation cover would be attained on sunny summer days with a decline on cloudy days.

These observation results clearly suggest that green walls were more effective in mitigating the influence of solar radiation and decreasing wall surface temperatures in warm weather and more so than insulating the wall in cold weather as Djedjig et al. (2015) predicted in their simulation study. Interestingly, the insulating performance of green walls decreased in cold and windy weather which is contradictory to the assumption made by Dunnett and Kingsbury (2008) that green walls would act as a wind barrier in the reduction of wind chill effects. The result can be explained by higher moisture content within the substrate in winter when plants were dormant and increased evaporation rate by wind which will help remove moisture from the air around the vegetation to allow for a greater amount of evaporation (Suzuki et al. 2007), although this requires further investigation.

Internal surface and Indoor air temperature

While the internal surface temperature behind green walls peaked at midday along with the indoor air temperature, the reference wall's surface temperature peaked hours after sunset between 20:00 and midnight throughout the year. The same time delay was observed in the indoor air temperature next to the reference wall. This delay occurred due to solar radiation transmitted to the exposed surface during the day and was then stored within the structure travelling through the wall at night. This was also observed on an uninsulated concrete wall by Cheng et al. (2010).

During the summer months, the green wall systems reduced daily peak temperatures of the internal wall surface by 1.5℃ and the daily minimum temperatures by 1.3℃; the figures were consistent with the findings of Cheng et al. (2010) and Eumorfopoulo and Kontoleon (2009) who stated that interior surface of the wall with vegetation cover constantly stayed 0.9℃–2.0℃ cooler throughout a day. During the win ter months, green walls increased the daily peak temperatures by 1.7°C and the minimum temperatures by 2.1℃.

The effects of the green walls on the internal wall surface were reflected in the indoor air temperature next to the wall although the impacts became less significant moving towards the centre of the room. The observation results showed that green walls increased the indoor air temperature throughout the year except for the summer months and the temperature increase in winter was larger than the reduction in summer. This is probably due to the current climate of the UK which requires heating in buildings for seven months of any given year with short spring and summer seasons. As mentioned in previous sections, July 2013 was exceptionally bright and warm for an average UK summer with a mean maximum temperature of 23.6℃. The reduction in ind oor air temperature near to the wall for the month of July was 1.5℃ on average compared to 0.8℃ in June and August with mean maximum temperat ures of 18.4℃ and 20.9℃. This result suggests that green walls w ould probably show a more significant impact in reducing indoor air temperatures in warmer climates than the UK.

System comparison

There was no significant difference in the effects among the four tested green wall systems in reducing peak temperatures of the external wall surface. The Trough system showed marginally better performance in increasing minimum temperatures of the external wall surface by around

0.5℃ compared to the others, possibly due to the large volume of the growing medium providing increased insulating benefits. The difference in monthly average temperatures amongst the four systems was also minimal on the internal wall surface and stayed within 0.4℃.

Neither plants nor an added insulation layer provided any additional peak temperature reductions on the external wall surface in summer; however, both elements were proven to be beneficial in increasing the insulation performance of green wall systems. During the autumn and winter months, the systems with an added insulation layer increased external wall surface temperatures throughout a day compared to the original green wall systems while the absence of plants decreased them. The effect was reflected on internal wall surface temperatures, even though the difference became less significant. These results demonstrated that adding insulation to existing green wall systems improves performance in increasing wall surface temperatures. Also, maintaining sufficient foliage cover is essential in optimising the insulating performance of the vegetation systems in cold weather and climates.

It should also be noted that the impacts of green walls on external wall surface temperatures were not necessarily always favourable. During the night, the green wall cover moderated the heat released through the external wall surface behind the systems throughout the year which increased the average daily minimum temperatures by 1.8℃ in the spring and summer months. The temperature increase was particularly significant in the systems with added insulation at 3.1℃. This adverse effect of added insulation under a green roof in summer was also observed by Yamada et al. (2004) who concluded it would not be an appropriate solution to improve the roof's year-round performance in the subtropical climate with hot and humid summer in Japan.

The green walls also reduced the average peak temperature of the external wall surface by 3.7℃ in the autumn and winter months. The reduction was less in the systems with added insulation although it still decreased it by 2.5℃ compared to the reference wall surface which was exposed to solar radiation during the day.

A warmer external surface in summer could potentially increase the heat gain through the wall depending on the temperature inside a building and also the energy load for air-conditioning when the internal temperature exceeds the occupants' comfort level. Contrary to this, a cooler building exterior surface in cold seasons can increase heat loss through the structure and energy load for heating. Therefore, in the next chapter, heat flow (gain and loss) transmitted through the observed walls during the twelve-month period as well as the energy loads are calculated and analysed using temperature data collected from this study. It investigates how the impacts of vegetation cover on the wall surface temperatures would influence the amount of heat transferred through the wall and also the potential reduction of thermal loads for cooling and heating that green walls could provide.

5.5. Conclusion

This chapter explained the field experimentation and results of the analysis using data collected in order to quantify the effects of green walls on wall surface and indoor air temperatures throughout four seasons in the UK climate. The focus of study was also to investigate factors that could influence the thermal performance of vegetation, and the main findings of these studies are as follows.

The effects of green walls on external wall surface temperatures:

- The green walls regulated the external wall surface temperature behind the installed systems. The average diurnal temperature fluctuation of the reference wall was 5.6–18℃ over the twelve months, and the vegetation reduced this to 1.5–3.8°C. (5.3.1)

- The green walls significantly reduced daily peak temperatures of the external wall surface and particularly in spring and summer. They decreased it by 12.1℃ in the warmest month wh en the mean maximum temperature was 23.6℃ and the mean peak temperature of the reference wall was 35.5℃. (5.3. 1)

- The degree of green wall's impacts on external surface temperatures was strongly correlated to the level of solar radiation and outdoor air temperature. (5.3.1 & 5.3.2)

- The green walls showed some insulating effects throughout the year; they increased the average daily minimum temperature of the external wall surface by 2.8℃ in the months when t he minimum outdoor temperature was below 5℃. (5.3.1)

- Green walls could have an adverse effect in increasing heat flow through the wall; they reduced the average peak surface temperatures by 2.5℃ in the winter months and increased the minimum temperature by 1.8℃ in the summer months. (5.3.1 & 5.4)

The effects on internal wall surface and indoor air temperature:

- The green walls reduced both daily peak and minimum temperatures of the internal wall surface by 1.4℃ in summer; they increased both daily peak and minimum temperatures by 1.7℃ and 2.1℃ in winter. (5.3.3)

- The green walls reduced the indoor ambient temperature near to the wall by 1℃ in summer and increased it by 2.3℃ in winter; the effects became less significant further away from the wall and those figures became less than half that quoted in the centre of the room. (5.3.4)

Influence of system variations, plants and additional insulation layer:

- Only a marginal difference was observed between all tested variations of green wall systems in reducing daily peak temperatures on both internal and external surfaces of the wall. (5.3.1 & 5.3.3)

- The trough system with a thicker substrate increased daily minimum temperatures of the external wall surface by 0.5℃ compared to the other systems in all seasons. (5.3.1)

- An added insulation layer increased the thermal resistance of the original green wall systems, increasing both daily peak and minimum temperatures of the external wall surface by 1.3℃ and minimum temperature of internal surface by 0.7℃ in the autumn and winter months. It also increased the minimum temperature of the external wall surface by 1.2℃ and the internal surface by 0.4℃ in the warmer months which could be an adverse effect in warmer climates than the UK. (5.3.1 & 5.3.3)

- Plants were found to be an important factor in optimising the insulating performance of green walls and when absent, the minimum temperatures of the external wall surface decreased by 1.5℃ and the internal surface by 0.2℃ in the autu mn and winter months. (5.3.1 & 5.3.3)

6. Numerical evaluation of the effects of green walls on the thermal performance of a wall

The temperature data collected during the experimentation explained in Chapter 5 was used in numerical studies to analyse the amount of heat gained and lost through the original wall structure during the twelve-month observation period. The aim of this chapter is to assess the thermal performance of green walls as a building insulation material in the climatic conditions of Sheffield, UK, by analysing the impact of vegetation cover on heat flow through a building wall behind it. The potential energy load reductions for heating and cooling that green walls can provide were also examined in this chapter to evaluate the economic viability of vegetation systems in regions where heating energy demand is a dominant factor.

The chapter begins with the introduction of existing studies and findings with regards to the effects of green cover on heat flow and energy loads of a building envelope described in Section 6.1. Section 6.2 explains the effects of green walls on heat flow through the wall while the results of numerical study for each tested system were compared against each other as well as the external insulation panel. The impact of vegetation cover on energy loads for space conditioning were then analysed in Section 6.3. In Section 6.4, the effectiveness of green walls as an insulation material in the UK climate is discussed and suggestions are made to optimise such thermal benefits of green walls. The main findings of the numerical studies were presented in Section 6.5.

6.1. Introduction

A number of studies looked at the effects of green roofs and walls in reducing heat transferred through building envelopes. When there is a temperature difference between external and internal surfaces of building materials, thermal energy will be transferred from warmer to cooler surfaces (Nojima and Suzuki, 2004). By moderating the influence of variable outdoor conditions on a building’s exterior surface, vegetation cover can decrease the temperature difference between the outer and inner surfaces of a building envelope. This consequently reduces heat transmitted through a building outer structure.

For the assessment of heat flow reduction effects, some existing studies used heat flux sensors to measure the actual heat exchange occurring on building surfaces. Measurements were taken either externally or internally. Heat flux data collected by Liang and Huang (2011) indicated that green roofs minimised heat inflow through an uninsulated roof on a summer day in Taiwan; the same effect was observed by Cheng et al. (2010) in a study using living walls in Hong Kong. In the cooler continental climate, Liu and Baskaran (2003) found that green roofs had a more significant impact in reducing heat gain in spring and summer than heat loss in cold periods of the year. Over a 22-month observation period, a green roof reduced daily heat gain by 95% and heat loss by 26%. They concluded that heat flux reduction would be more significant in warmer regions as the energy demand in Ottawa, Canada, is predominantly for heating.

Other studies took a numerical approach to determine heat gained and lost through the envelope using temperature measurements collected in field experiments. In those studies, heat flow was calculated based on the temperature difference between external and internal surfaces of a roof or wall structure.

A numerical study carried out in Hong Kong by Jim and Peng (2012) found that a green roof eliminated heat gain through the roof in summer and also increased the amount of heat loss by approximately threefold when compared to the exposed reference roof. Significant heat flow reductions due to vegetation cover in the subtropical climate were also reported by Wong et al. (2003) and Sonne (2006) on green roofs, and by Eumorfopoulo and Kontoleon (2009) on green walls. Results from Spolek (2008)'s numerical study in the temperate climate of Portland, USA, were similar to the findings of Liu and Baskaran (2003), showing that a green roof reduced the average hourly heat flow through the roof structure by

72% during a mild and dry summer whilst the reduction in winter was significantly lower at 13%.

In some studies, heat flow was interpreted as a factor to determine the energy load of an envelope for mechanical space conditioning. Kamitomai and Tarumi (2007) analysed the energy loads of a vegetated roof using recorded heat flow data in Kanazawa, Japan. In this study, the reduction of unfavourable heat flow—heat gain in air-conditioning seasons and loss in heating seasons—occurred between 9:00 to 17:00 was considered to be the reduction of thermal loads for mechanical heating and cooling. They found that the green roof with a 240mm substrate layer reduced the annual energy load due to heat flow through the roof by 43%, again, primarily due to the substantial heat gain reductions in summer rather than heat loss in winter. Jim and Peng (2012) calculated the potential daily energy load reduction for air-conditioning by assuming the accumulated heat gain through the roof over a 24-hour period to be the daily cooling load, and concluded that the green roof reduced energy loads due to heat flow through the roof by 0.9 kWh/m^2 on a bright summer day in Hong Kong. In a study conducted by Ochiai et al. (2006) in Yokohama, Japan, it was reported that a green roof reduced the daily cooling load by 23% in summer based on the difference in recorded electricity consumption for two tested rooms (one with green roof cover) with air-conditioned set at the same temperature for 24 hours. However, as buildings are not often occupied throughout the day, those figures may not accurately represent the potential energy reduction for most buildings, even in similar climatic conditions.

In this study, heat flow was calculated using temperature data collected in a field experiment described in the previous chapter in order to assess the performance of four tested green wall systems as an external insulation material in the current climate of Sheffield, UK.

For the energy load assessment, heating and cooling loads were determined by the amount of energy exchanged between the external wall surface and indoor air through the wall structure, a method previously adopted by Kimura et al. (2005), Liao and J.L. (1998) and Eumorfopoulo and Kontoleon (2009). The thermal loads were considered to be the amount of energy required to keep the indoor air temperature within the range of the CIBSE's recommended room temperatures for educational buildings. Also, as the occupancy rates and requirements for heating and cooling are different depending on building type, the analysis was divided into two twelve-hour periods of a day (daytime and night-time).

6.2. Effects on the heat flow through the wall

In this study, heat travelling through each test bed section of the wall was calculated using temperature measurements collected from the interior and exterior surfaces and the results for each system were compared against each other in order to investigate the influence of system variation and factors including absence of plants and added insulation layer. The performance of green walls in reducing heat gain and loss were also compared against that of an external insulation panel to assess the vegetation systems as building insulation material. A section of 'Climbers' testbed (ultimately excluded from the experimentation) where plants failed to provide foliage cover was considered as an externally insulated wall for the purposes of this analysis. It consisted of the original wall construction covered with 100mm thick Polyisocyanurate insulation board (λ=0.022W/mK) and a layer of water proof membrane for the duration of the experiment.

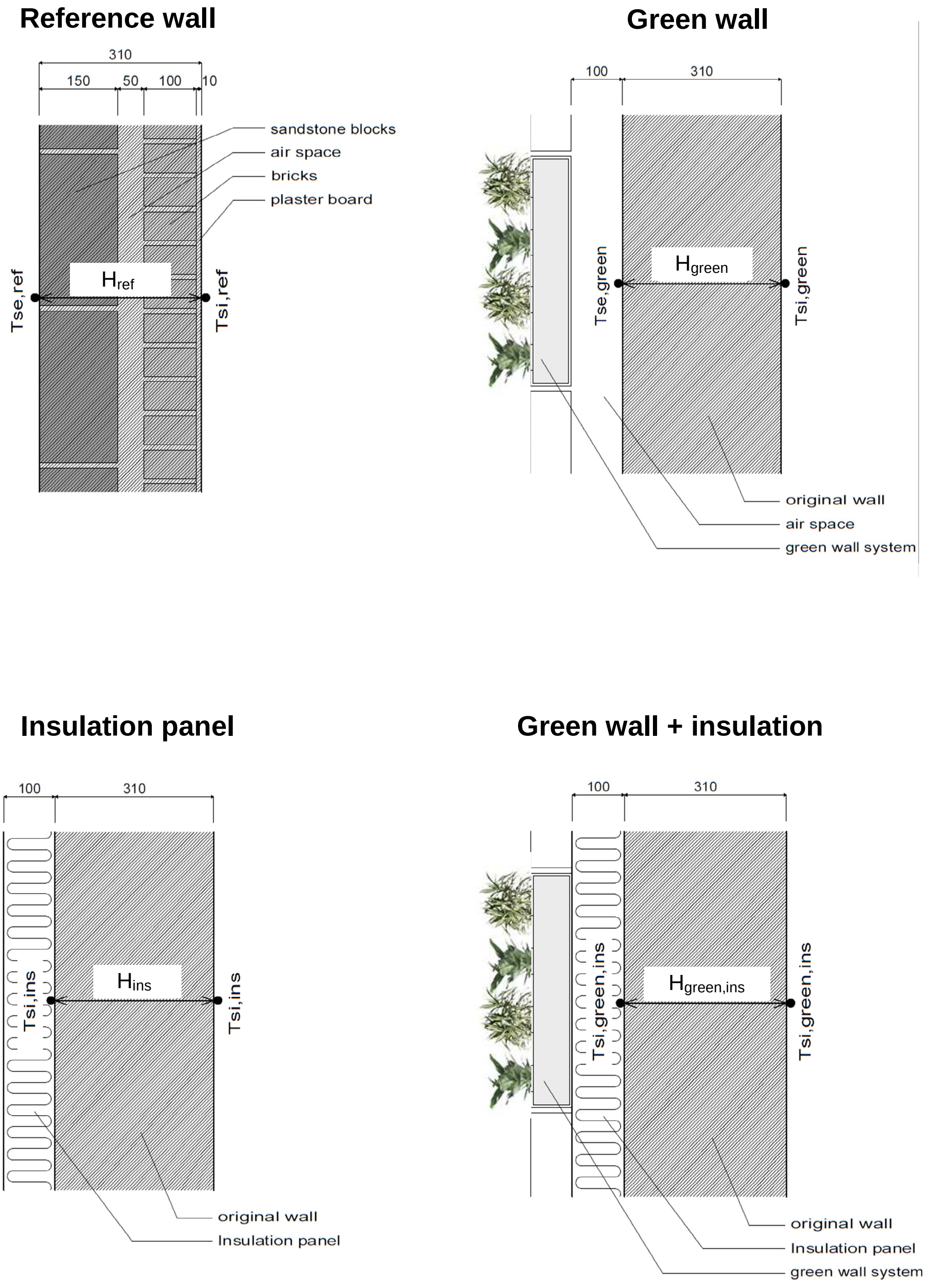


Figure 6.1 Sectional drawings showing the locations where temperature measurements used in heat flow calculation were taken on the wall

6.2.1. Calculation of the heat flux

The equations used to acquire the total amount of heat transferred through the building's external wall structure in a 24 hour period are explained below. Firstly, the thermal resistance *Rt* [m^2·K/W], and the thermal transmittance *K* [W/m^2·K] of the wall structure were determined by the following equations based on the physical thickness and thermal properties of the walls makeup and components:

$$Rt = R\lambda 1 + R\lambda 2 + \cdots\cdots\cdots R\lambda n \tag{6.1}$$

$$R = \frac{T}{\lambda}$$

λ: $Thermal\ conductivity\ of\ the\ material$

T: $Thickness\ of\ the\ material$

$$K = \frac{1}{Rt} \tag{6.2}$$

Then, the heat flow *Q* [W/m^2] travelling through the monitored sections of the wall structure per hour was obtained as follows:

$$Q = K(Tse - Tsi) = K(Tse, mean - Tsi, meatn) \tag{6.3}$$

Tse,mean and *Tsi,mean* are the hourly mean temperatures of external and internal surfaces of the wall, and this equation calculates the heat travelling through the wall from the external to the internal surface.

Based on this equation, the daily heat flow for a 24 hour period Q_{24} [W/m^2] was defined by the following equation with n representing each measured hour:

$$Q_{24} = 24K \sum_{n=1}^{24}(Tse, n - Tsi, n) \tag{6.4}$$

The physical and thermal properties of components of the monitored wall which were used for heat flow calculations are presented in the table below. The configuration of the wall structure and physical values were determined from the CAD drawings and measurements taken prior to the study. (See Appendix C for the calculations of thermal resistance *Rt* [$m^2 \cdot K/W$] and the thermal transmittance *K* [$W/m^2 \cdot K$] of the wall structure used for the data analysis)

Table 6.1 External wall components and their thermal conductivity

Wall components	Thermal conductivity: λ (W/m·K)	Thickness: T (m)
Sandstone	1.4	0.15
Air gap	0.28*	0.05
Brick	0.56	0.1
Plaster board	0.21	0.015

*The value specified by the Building Research Establishment (BRE) for the thermal resistance of unventilated air space in cavity wall construction ($0.18m^2K/W$) (Anderson, 2006) was applied in this study.

The thermal conductivity of the original wall construction derived from the above calculation was $1.86W/m^2K$. This is equivalent to the value of a cavity wall without insulation constructed before 1965 when the required standard for a wall was set at $1.7W/m^2K$ in the UK. This is consistent with the fact that the building was constructed around that period and the part of the building used for the experiment had not been altered or updated since.

In order to minimise the effects of occupancy and also mechanical heating during the winter period, calculation of heat flow was conducted using data collected during weekends and holidays only when the recorded occupancy of the observed classrooms was less than ten and the heating was switched off. During those periods, all the windows and window blinds on the south-east facing wall of the classrooms were closed to minimise the influence of natural ventilation and incoming solar radiation through the glazing.

6.2.2. Impacts on heat gain and heat loss through the wall

The majority of heat flow occurring through the reference wall section during the twelve-month observation period was in an outward direction, meaning heat was travelling from the internal space to the outdoor air through the wall construction. The heat gain accounted for only 12.6% of the total heat flow through the reference (original) wall and the majority of heat gain occurred between May and September as shown in Figure 6.2. The amount of heat loss through the reference wall was greater than the heat gain in all twelve months including July, the warmest and brightest month during the experimentation, and greater heat loss was observed between November and March when the monthly mean temperature was below 6℃ and the total solar radiation was less than 10KW/m^2 (Figure 6.3). This demonstrates that energy loads in Sheffield were predominantly for heating in autumn and winter to compensate for heat escaping through the envelope due to the low outdoor air temperature.

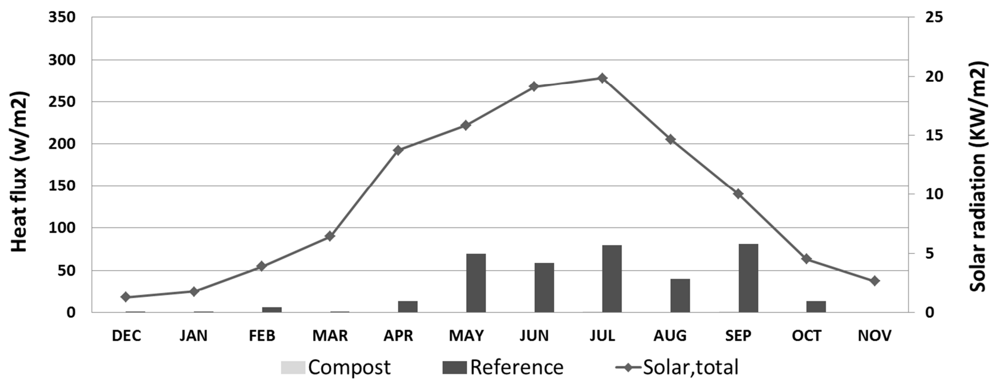


Figure 6.2 Daily mean heat gain through the wall for each month

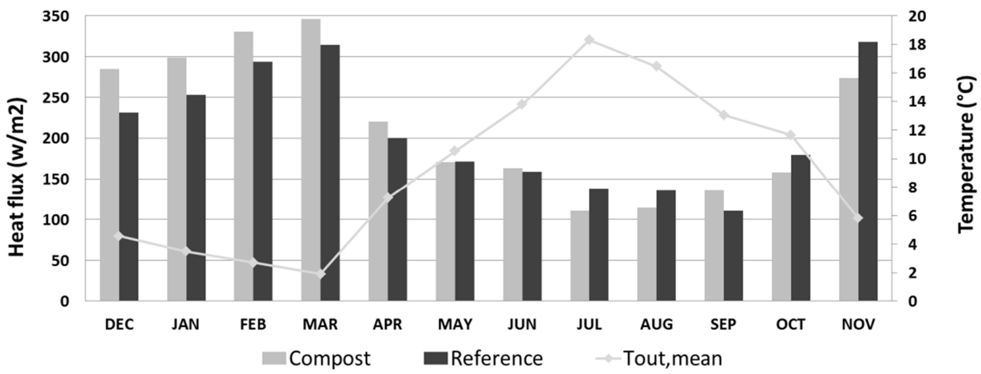


Figure 6.3 Daily mean heat loss through the wall for each month

The green wall systems almost eliminated heat gain through the wall throughout the year. However, the differences in daily average heat loss between the reference wall and tested green walls were insignificant and in some months, vegetation cover increased the heat loss through the wall structure. This is because in autumn and winter, the external surface of the reference wall received solar radiation and became warmer in the afternoon which reduced the amount of heat escaping through the wall. Temperatures of the wall surface behind the green wall systems on the other hand, were kept constant throughout the day as the vegetation eliminated the influence of solar radiation. Since the indoor temperature of unoccupied and unheated rooms also did not fluctuate, the amount of heat loss remained constant throughout the day. Although green walls marginally reduced the heat lost through the wall from midnight to early morning (Figure 6.4), the night-time heat loss reduction was too small to compensate for the difference in daytime heat loss. As a result, green walls increased the daily mean heat loss during the winter months as shown in Figure 6.3.

Figure 6.5 demonstrates similar but more obvious effects of green walls reducing solar radiation gain during the day and insulating the wall at night observed during the summer months. On a summer day, both warm ambient air and sunlight increased the surface temperature of the exposed reference wall and the heat travelled inwards towards the cooler indoor air.

The external wall surface behind the vegetation was kept cooler than the internal wall surface throughout the day, resulting in constant heat loss through the wall. This ‘cooling effect’ was most significant between 13:00–16:00 when the reference wall experienced overheating due to solar radiation. During the night, the outer surface temperature of the reference wall rapidly decreased being exposed to the cooler ambient air. However, the green walls retained a stable surface temperature and thus, greater heat loss was observed on the reference wall.

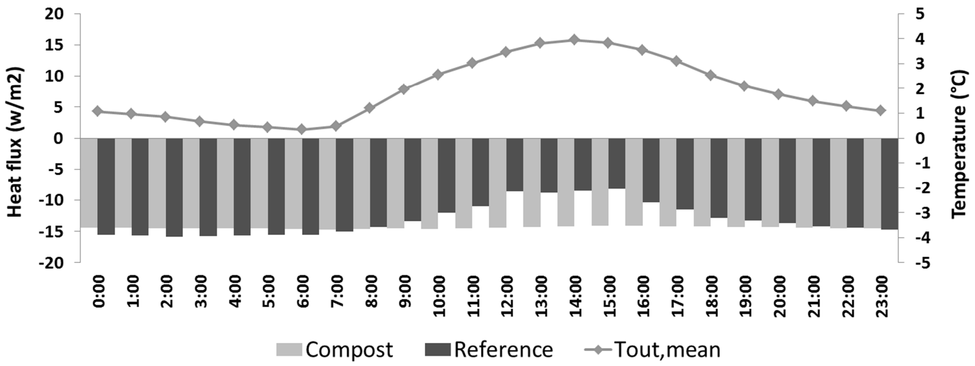


Figure 6.4 Hourly mean heat flow through the wall for the month of March

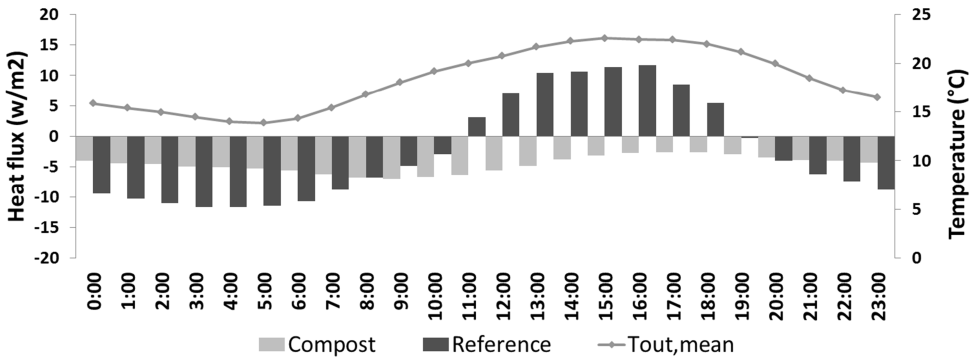


Figure 6.5 Hourly mean heat flow through the wall for the month of July

System comparison

Table 6.2 shows that all tested systems minimised the influence of solar radiation gain and virtually eliminated heat travelling inwards through the wall in the spring and summer months. Significant heat gain was not observed through any of the wall sections including the reference wall for the rest of the year. In autumn and winter, all four green wall systems recorded larger heat losses compared to the reference wall as their effects in reducing solar gain during the day resulted in increasing heat loss. The results of four systems showed marginal differences in terms of the actual amount of heat flow occurring through the wall construction behind them. The Ivy screen, which did not contain a substrate layer, was slightly more susceptible to solar heat gain and higher external wall surface temperatures resulting in marginally increased heat gain and also a reduction in heat loss compared to the other systems in summer. Trough and Hydroponic systems showed slightly better insulating performance which could be due to the insulation properties of the substrate in both cases (80mm thick horticultural Rockwool in the Hydroponic and maximum 150mm thick compost layer in the Trough system).

Table 6.2 Seasonal daily mean heat flow for the respective green wall systems and the reduction rates against the reference wall

		Compost	Hydroponic	Trough	Ivy screen	Reference
Spring & summer	**Daily mean heat gain (W/m^2) (April-September)**	0.2 (-99.6%)	0.1 (-99.8%)	0.3 (-99.5%)	1.2 (-97.8%)	56.9
	Daily mean heat loss (W/m^2) (April-September)	153 (±0%)	148 (-3%)	142 (-7%)	141 (-8%)	153
Autumn & winter	**Daily mean heat loss (W/m^2) (October-March)**	282 (+6%)	267 (+1%)	272 (+3%)	280 (+6%)	265

Influence of plants and added insulation

Similar to the result of the system comparison explained above, all three variations of green wall systems equally minimised heat gain through the wall during the spring and summer months, although added insulation marginally increased daily mean heat gain and a lack of plants decreased it compared to the original green wall systems. As the influence of both foliage mass and insulation panels on heat gain were minimal, the increase and reduction in heat flow was mostly due to the insulating effects of plants and the additional insulation. In all four tested green wall systems, extra insulation panels reduced heat loss through the wall and a lack of plants increased it compared to the original form of systems in all four seasons. On average, extra insulation panels decreased daily mean heat loss by 11% and the absence of plants increased it by 8% compared to the original systems during autumn and winter months. These figures were slightly higher in warmer months, and the reduction of heat loss due to additional insulation suggests a potential negative impact in warmer climates compared to the UK (Table 6.3).

Table 6.3 Daily mean heat flow for each variation of green wall system (average between four systems) and the reduction rates against standard green wall systems (heat loss only)

		Green wall	Green wall (+insulation)	Green wall (no plants)
Spring & summer	Daily mean heat gain (W/m^2) (April-September)	0.5	0.2	3.0
	Daily mean heat loss (W/m^2) (April-September)	146	125 (-15%)	160 (+10%)
Autumn & winter	Daily mean heat loss (W/m^2) (October-March)	275	244 (-11%)	298 (+8%)

6.2.3. Comparison with an external insulation panel

In this analysis, a section of ‘Climbers’ test bed which had an insulation board covering the original wall construction without any foliage cover was considered to be an ‘externally insulated wall’ and heat flow through the original wall construction behind the insulation was calculated using data collected from this section. The results were compared against that of the green wall systems in order to assess the performance of vegetation systems as building insulation material.

Between October and March when the heat flow through the reference wall was primarily heat loss, the external insulation was extremely effective in minimising the influence of weather elements. It retained the outer surface temperature of the original wall construction at a higher temperature than the exposed reference wall the majority of the time except for few hours in the afternoon. As described in the previous section, the green wall systems increased the daily heat loss in autumn and winter by not providing enough insulating effects to compensate for the moderation of solar gain during the day. In the case of the insulation board, the increase of daytime heat loss was negligible compared to the amount of heat loss reduced against the reference wall throughout the day (Figure 6.6). The insulation board minimised the effects of solar radiation as did all other tested systems during the summer months. However, it also reduced the amount of heat loss compared to the green walls by preventing heat escaping through the wall particularly during the night (Figure 6.7).

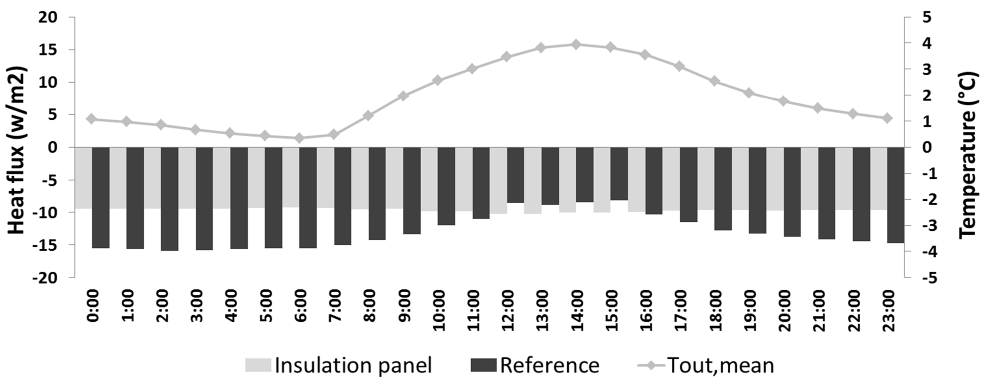


Figure 6.6 Hourly mean heat flow through the wall for the month of March

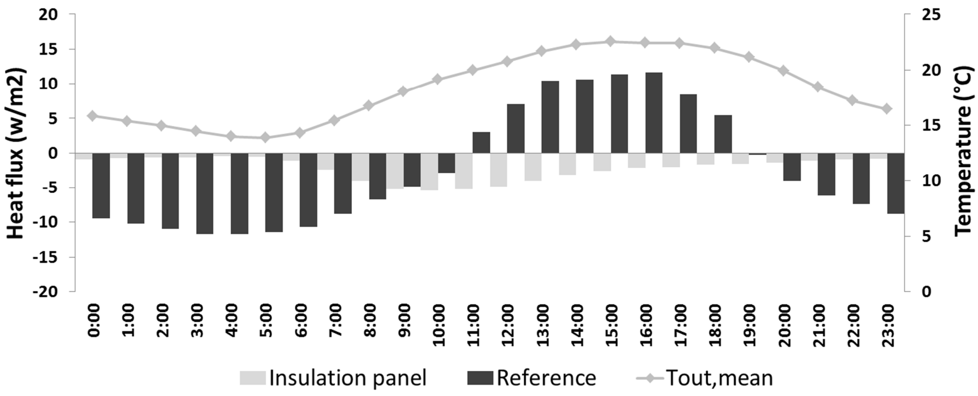


Figure 6.7 Hourly mean heat flow through the wall for the month of July

The resulting heat flow comparison between the insulation board and green walls revealed that the external insulation was actually more effective in reducing heat flow (total heat gain and loss) through the original wall construction behind it compared to any variations of tested green wall systems. The daily average heat flow through the wall covered by external insulation panel was even lower than the Trough system with the same insulation panel behind it which showed the best performance in reducing heat loss among all the tested systems.

The comparison of reduction rates of heat flow against the reference wall showed that the difference in performance between the green wall systems and the external insulation panel were largely due to the insulating effects in all seasons. As Table 6.4 shows, the original green wall systems were already highly effective in minimising heat gain and no significant improvements could be made by adding insulation or being replaced by an insulation board. Green walls showed minimal insulating effects and even increased the amount of heat loss through the wall during the autumn and winter months. Although inserting an insulation board behind the vegetation systems improved the overall performance in reducing heat loss through the wall, the best results were obtained from the external insulation panel without vegetation cover. While the insulation board reduced heat loss through the wall by a quarter between October and March, green wall systems with insulation panel only reduced it by 5–11% and original form of green wall systems increased it by 1–6%.

Table 6.4 Seasonal daily mean heat flow and reduction rate against the reference wall for the green wall systems and external insulation

		Average of 4 original systems	Average of 4 systems + insulation	External insulation panel	Reference
Spring & summer	**Daily mean heat gain (W/m^2) (April-September)**	0.5 (-99.1%)	0.2 (-99.7%)	0.3 (-99.5%)	56.9
	Daily mean heat loss (W/m^2) (April-September)	146 (-4%)	125 (-18%)	95 (-38%)	153
Autumn & winter	**Daily mean heat loss (W/m^2) (October-March)**	275 (+4%)	244 (-8%)	199 (-25%)	265

6.3. Effects on the energy loads of a wall for heating and cooling

In the previous section, heat travelling through the wall construction was calculated and analysed in order to evaluate the performance of green wall systems as external building insulation material reducing heat flow through a wall behind them. In this section, analysis was carried out on the actual amount of heat entering into and escaping from the indoor air through the wall during the twelve-month observation period and how it translated into economic values, meaning reduction of energy requirement for heating and air-conditioning due to the green wall systems. Economic benefits of the respective systems were assessed with consideration to installation costs, maintenance requirements and the potential energy savings for heating and cooling.

6.3.1. Calculation of thermal loads

When indoor air temperatures need to be mechanically increased or reduced in order to achieve a certain comfort level required by a buildings occupants, the amount of energy required for HVAC system is called thermal loads (Manso and Castro-Gomes, 2015). The heat coming into and escaping from the internal space through the building envelope can both increase and decrease thermal loads depending on the difference between the external wall surface temperatures and indoor air temperature. A high thermally performing wall should reduce heat entering into the building in summer and prevent it escaping in winter.

In this study, heating and cooling loads were determined by the amount of energy exchanged between the external wall surface and indoor air through the wall structure by using recorded temperatures. All data recorded during the twelve-month experiment, including the period when observed classrooms were occupied and heated, was included in the thermal load calculation. This is because higher internal air temperatures result in a larger heat loss through the building envelope (Nojima and Suzuki, 2004), and the calculation excluding data from heated periods may not represent the thermal load of the building in use. Since the results did not exclude the influence of occupancy, the study was conducted to solely assess the actual performance of tested green wall systems on the observed building in Sheffield for the period of twelve-months.

The equations used to acquire the total thermal loads through monitored walls in a 24 hour period are explained below.

The thermal resistance *Rt* [m^2·K/W] for the calculation was derived by adding the factor of thermal conductivity of the indoor ambient air *a* [W/m^2·K] to the equation (6.1).

$$Rt = \frac{\mathrm{T}}{\lambda} + \frac{1}{a} \qquad (6.5)$$

$$= \mathbf{0.648\ m^2{\cdot}K/W}$$

a=Thermal conductivity of indoor air: 9.3[W/m²·K]

The hourly thermal loads Q_{load} [W/m^2], which is the heat transferred from the external wall surface to indoor air through the wall structure per hour were obtained as follows:

$$Q_{load} = K(Tse - Tin) = K(Tse, mean - Tin, mean) \qquad (6.6)$$

Tse,mean and *Tin,mean* are the hourly mean temperatures of the external wall surface and indoor air. The equation defines the heat travelling inwards through the wall from the external surface to the internal space.

Based on this, the daily thermal load for a 24 hour period $Q_{load,24}$ [W/m^2] was calculated using the following equation with *n* representing each measured hour:

$$Q_{Load,24} = 24K \sum_{n=1}^{24}(Tse,n - Tin,n) \qquad (6.7)$$

Calculations of cooling and heating loads were carried out to meet the CIBSE's recommendation for room temperatures in educational buildings, which are between 19–21℃ in winter and 21–23℃ in summer. (CIBSE, 2008). The thermal loads determined by the calculations were considered to be the amount of energy required to be compensated for by mechanical heating and cooling in order to keep the indoor air temperature within the range stated above.

The definitions of heating and cooling loads in this study are as follows.

Cooling loads

Heat travelling inwards from the external wall surface to indoor air was considered as cooling loads in the 'air-conditioning period' of the year between:

- The months from June to September

When:

- The indoor air temperature exceeded the occupants' comfort level of 23℃

Thermal loss (heat travelling from the internal space outwards) through the wall during the air-conditioning period was considered as a reduction of cooling loads when the indoor air temperature exceeded the occupants' comfort level of 23℃.

Heating loads

Heat travelling outwards from the indoor air to the external wall surface was considered as heating loads in the ‘heating period’ of the year between:

- The months of October to April

When:

- The indoor air temperature was below the occupants’ comfort level of 19℃ between the hours of 20:00 and 8:00
- All hours between 8:00 and 20:00

Since the classrooms were mechanically heated during the heating period, indoor air temperatures exceeded the comfort level of 19℃ for the majority of the time. Thus, measurements of all hours during the day (8:00 -20:00) were included in the calculation. Thermal gains (heat travelling from the external wall surface inwards) in the heating period were considered a reduction of heating loads when the room temperature was below 19℃.

May was considered neither a cooling nor heating period, and the measurements for that month were not included in the thermal load calculations.

6.3.2. Reduction of annual energy loads for heating and cooling

The analysis of energy loads were divided into two periods, daytime (between 8am and 8pm) and night time (8pm and 8am). This was due to the occupancy rates and requirements for heating and cooling being different depending on building type. For example in offices, the energy load is higher in the daytime whilst in domestic buildings, the night time energy load is higher, particularly for heating in winter.

Importantly, the energy loads for internal space conditioning discussed in this section are based on the thermal flow through the wall ONLY and the mentioned reduction rates based on the energy loads of the reference wall only, not the energy consumption for the entire building.

The results of all four original systems were similar in terms of daytime thermal load reduction throughout the year. The green wall systems often increased daytime energy loads during the heating seasons (October-April) by minimising solar radiation gains through the wall. An insulation panel behind the green wall system reduced the energy loads for heating during the winter months with the increased insulation compensating for the negative cooling effects at midday. In summer (June-September), all variations of the systems significantly reduced the energy load for air-conditioning throughout the season. The vegetation kept the external wall surface cooler than the indoor air which resulted in heat being continuously lost through the wall structure during the day whilst a large amount of heat was gained through the reference wall. The impact was particularly significant in July, the hottest and brightest month of the year (Figure 6.8).

As for night time thermal load reduction, all four systems reduced the energy loads for heating in autumn and winter. Systems without plants had less impact on the heating loads compared to the other variations and in the case of the Compost system, it increased the thermal loads for December and February. The system with an added insulation layer showed the best result in reducing heating loads in winter. During the air-conditioning period, these insulating properties had a slightly negative effect, increasing the cooling loads during the warmer months. However, the initial energy loads for cooling during the night were minimal in Sheffield except for July 2013 which was an exceptionally warm month. The average indoor air temperature exceeded the occupants' comfort range at 24.8℃ whilst the average outdoor air temp erature was 18.3℃.

During comparatively warm periods, the system with extra insulation showed a noticeable negative impact on thermal loads by reducing the heat escaping through the wall (Figure 6.9).

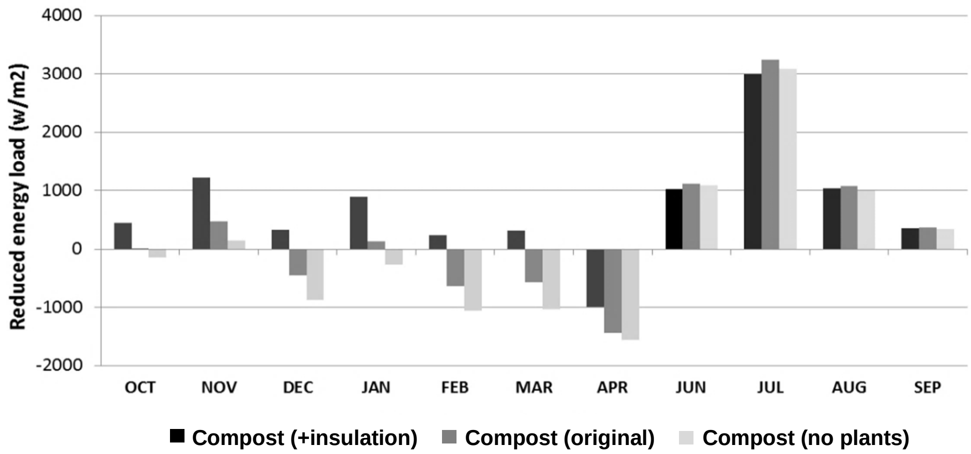


Figure 6.8 Reduction of monthly energy loads for heating and cooling during the day (8am–8pm)

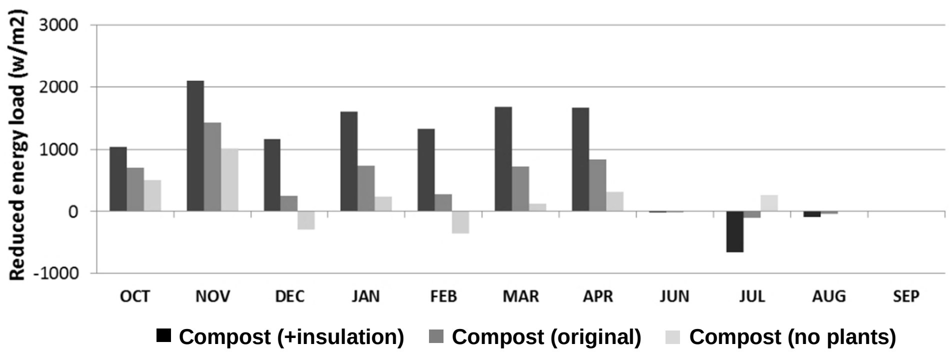


Figure 6.9 Reduction of monthly energy loads for heating and cooling during the night (8pm–8am)

All original green wall systems reduced the annual daytime cooling load. In all four cases, vegetation cover not only reduced the thermal gain but also increased the thermal loss through the wall in summer. The amount of thermal loss through the wall behind the green walls during the day was over four times the amount of thermal gain through the reference wall, demonstrating the effectiveness of vegetation in reducing the air-conditioning load. The impact of green walls on cooling loads at night was minimal as the initial night-time energy load for air-conditioning was negligible in Sheffield as previously described.

Green walls reduced annual night-time heating loads as a result of heat flow through the wall by 12–17%; however, they also increased daytime heating loads by 6–9%. This resulted in a reduced overall impact for green walls on the energy load during the heating seasons (Figure 6.10).

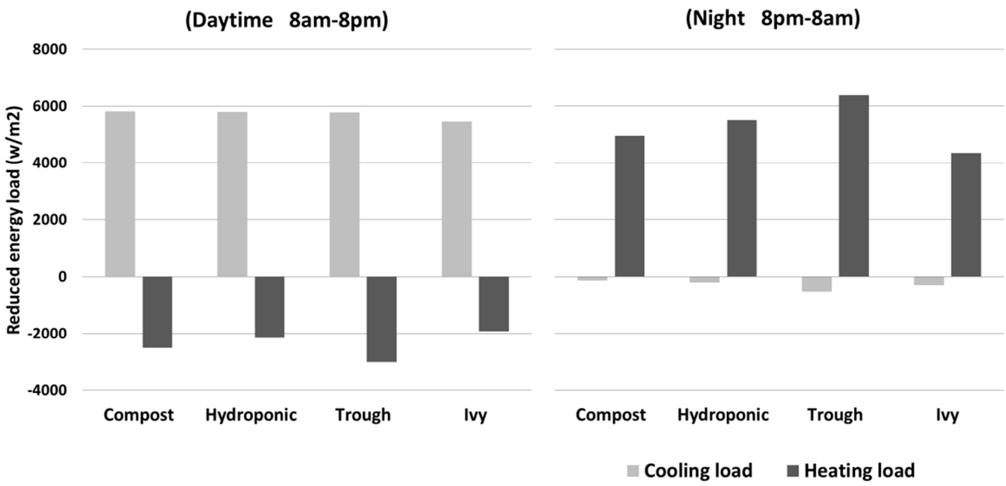


Figure 6.10 Reduced annual energy loads for heating and cooling during the day and night due to the original green wall systems

The comparison of the annual energy load reductions revealed that all variations of tested systems had similar impacts on reducing the air-conditioning loads. This indicates vegetation cover can reduce the annual cooling loads regardless of the type of system. The original form of green wall systems reduced larger amounts of energy load for cooling than heating despite the fact that the cooling load accounted for less than 10% of the total annual energy loads of the observed wall. This highlighted their superior performance in reducing radiation heat gain compared to the prevention of heat loss.

The trough system showed the best insulating performance in reducing heating loads. This could be because the system consisted of a deeper substrate layer than the other living wall systems, and thus had a generalised increase in thermal resistance, providing better insulation. The ivy screen showed the least impact on reducing heating loads as it only provided a foliage cover over the wall. The absence of a substrate layer and consequently its thermal resistance affected the insulating performance of this system.

The additional insulation to the system proved to be effective in improving the insulation performance of the existing green wall systems by reducing the annual heating loads by more than threefold compared to the standard system. This is due to the fact that in the current climate in Sheffield, UK, the majority of annual energy load requirements were for heating in prolonged winter periods and the cold spring months. Insufficient foliage cover reduced insulating effects across all green walls. Systems without plants did not provide enough heat loss reduction to compensate for the negative daytime heat gain reduction in cold weather as compared to the other two variations, and as a result, increased the annual energy loads for heating. The results indicate that both plants and the extra insulation layer were key factors in improving the insulating performance of green wall systems (Figure 6.11). The results of system comparison echo the findings of the heat flow studies in the previous section.

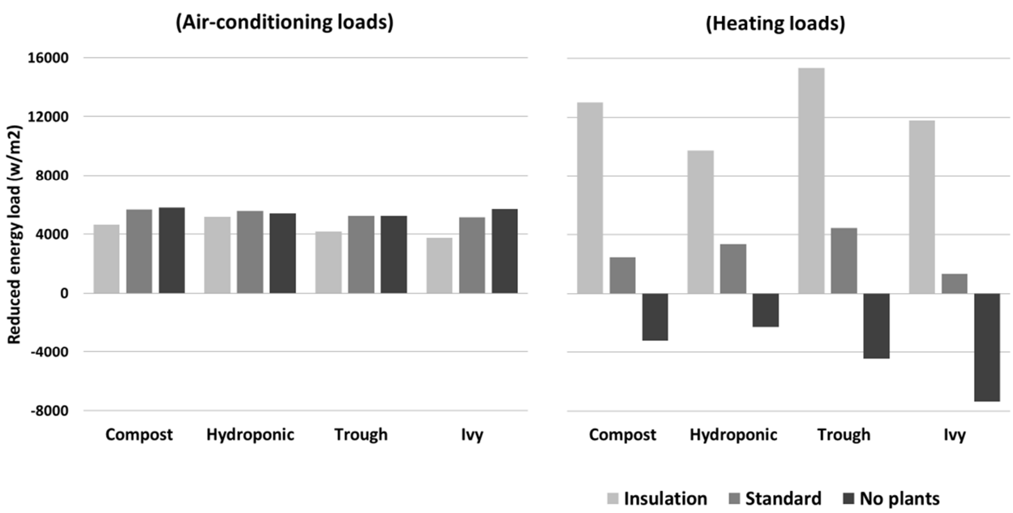


Figure 6.11 Reduced annual energy loads for air-conditioning and heating ('No plants' for ivy screen defines little foliage cover)

Table 6.5 shows the annual energy loads of the wall and electricity costs for heating and air-conditioning that a square meter of each system reduced for the duration of the study. The electricity cost was calculated using the national average per unit cost in the UK which at the time of this study (May 2014) was £0.14/kWh (UK Government, 2014).

The actual reduction of electricity costs appear to be remarkably insignificant, and results show that none of the systems would recover the initial installation cost through the cooling and insulation effects on a wall, let alone provide savings in energy costs within their life span in the current climate in Sheffield (Installation costs and system life span are explained in Table 5.4). This is, again, due to the fact that the majority of annual energy loads in the Northern European climate and particularly in the UK is for heating. Green wall systems have less of an effect in reducing the heating loads compared to the cooling loads as the previous section also demonstrated.

Table 6.5 Reduction of annual energy loads and electricity costs for heating and air-conditioning based on the recorded data

	Reductions of annual energy loads (kWh/m^2)		
	Insulation	Standard	No plants
Compost	17.68	8.14	2.59
Hydroponic	14.92	8.94	3.12
Trough	19.54	9.70	0.80
Ivy screen	15.51	6.49	-1.66
	Reductions of annual electricity cost (£/m^2)		
	Insulation	Standard	No plants
Compost	2.48	1.14	0.36
Hydroponic	2.09	1.25	0.44
Trough	2.74	1.36	0.11
Ivy screen	2.17	0.91	-0.23

6.4. Summary and discussion

Results of the numerical studies demonstrated that green walls were more effective in reducing daily heat gain through the wall than heat loss. During the day, green walls almost eliminated solar radiation gain and also increased heat loss through the wall throughout a year. This effect significantly reduced the energy load for air-conditioning in summer although in return, it increased the daytime heating load in winter. Vegetation cover provided insulation during the night, decreasing the amount of heat escaping through the wall; however, this effect was offset by the increase in daytime heat loss in winter and also slightly increased the night-time air-conditioning load in summer. As a result, the calculated annual air-conditioning load reduction was higher than the heating load reduction. This was rather surprising as the majority of energy load in Sheffield, UK, was for heating and the heat gain only accounted for 12.6% of the total heat flow occurring through the reference wall during the twelve-month observation period. Heat gain reduction was more significant in the warmer and brighter months, which indicated that green wall systems would be highly effective in reducing the air-conditioning loads in regions where the majority of annual energy loads are for cooling. However, the impacts of vegetation systems on the energy load are minimal in colder climates such as the UK where building energy consumption is primarily for heating due to the limited insulating performance and negative daytime heat gain reduction during cold weather. These results echo the conclusion of green roof experiments conducted by Liu and Baskaran (2003) and Spolek (2008) in the temperate and continental climates of North America.

The results of both heat flow and energy load calculations for the four original systems were comparable throughout a year. In general, the Trough system demonstrated slightly better insulating performance due to the thermal resistance of a deeper substrate layer and the Ivy screen showed marginally less impact on the heat loss reduction as it only provided a foliage cover without a substrate layer.

Adding an insulation layer to the systems reduced daily mean heat loss by 11% and the absence of plants increased it by 8% on average compared to the original green wall systems in the autumn and winter months. In warmer month, these figures were slightly higher, which demonstrated that an additional insulation layer will be beneficial in increasing the thermal resistance of green wall systems in climates with high heating energy demands, although this insulating effect can have a negative impact on night-time cooling loads in air-conditioning load dominated regions.

The comparison between the performance of the insulation panel and the green wall systems revealed that the external insulation was actually more effective in reducing heat loss through the wall construction behind it. Whilst the insulation board reduced heat loss by 25% between October and March, green walls with an insulation panel only reduced it by 5–11% and the original systems adversely increased it by 1–6%.

In spring and summer (April-September), all tested systems reduced heat gain through the wall by over 99%. However, it also reduced heat loss by insulating the wall particularly at night. Insulating effects of the original green walls were negligible in summer whilst both the systems with added insulation and the external insulation panel decreased the amount of favorable heat loss by 18% and 38% respectively.

The results of the numerical studies imply that although adding an extra insulation layer would be an inexpensive solution in increasing the insulating properties of the system, it appears unlikely to help recover the initial installation costs of green walls by thermal effects alone within their life span and in the current climate of Sheffield, UK. Thus, an external insulation panel, which is considerably simpler and economical to install and maintain, will be a better solution in improving the thermal performance of a wall in climates where heating loads are a dominant factor. Also, the fact that the insulation panel showed better heat loss reduction effects compared to the green walls with insulation panels suggests that vegetation systems may not provide additional insulating benefits to an external insulation material and may also decrease the performance of externally pre-insulated walls. This potential adverse effects in cold weather was also observed by Saki et al. (2006) in Japan where a green roof increased the amount of heat loss through both insulated and uninsulated roofs.

As a number of existing studies have suggested, the true potential of green walls will be best utilised in climates where cooling loads are dominant. Green walls will be highly effective in reducing radiation gain during the day with minimum insulating effects at night, whilst conventional insulation material can undesirably increase night-time cooling loads by inhibiting heat lost through the wall. The same conclusion was drawn by Yamada et al. (2004) in their study that compared the performance of green roofs to a conventional external roof insulation material.

Since the most significant cooling load reduction of green walls was observed between 13:00–16:00, vegetation cover could be a useful solution in reducing peak time energy loads for air-conditioning. The study also found that all tested green wall systems would provide comparable effects in reducing cooling loads due to heat flow through the wall including climber screens which are relatively inexpensive to install and require less maintenance and irrigation (Please refer to 7.4.1). Hence, when one focuses on the air-conditioning load reduction as a priority, choosing systems with the lowest initial costs and subsequent maintenance would be beneficial. This conclusion validates the results of life-cycle cost analysis with focus on the potential heating and air-conditioning load reductions carried out by Ottelé et al. (2011) that indicated only green façades with climbing plants were economically viable option even in the Mediterranean climate due to the high initial and running cost of living walls, and in the temperate climate, both living walls and green façades showed higher environmental costs than the benefits.

6.5. Conclusion

This chapter explained the numerical studies conducted to investigate the effects of green walls on heat flow through the wall construction and energy loads for cooling and heating. The main findings of these studies are as follows.

- All four tested green walls reduced over 99% of daily mean heat gain in spring and summer; however, minimising solar radiation gain resulted in 1–6% increase in daily mean heat loss in cold seasons. (6.2.2)

- Green walls eliminated the cooling load due to heat flow through the wall in the current climate in Sheffield. The impacts of green walls on the heating loads were minimal as the night-time heat loss reduction of 12–17% was offset by undesirable daytime heat gain reduction of 6–9%. (6.2.2 & 6.3.2)

- Plants were found to be an important element in optimising insulating performance of green walls as their absence increased heat loss through the wall by 8% in autumn and winter. (6.1.2 & 6.2.2)

- Adding an insulation panel improved the performance of existing green walls in reducing heat loss as they decreased heat flow through the wall by 11% in autumn and winter although the same insulation panel without vegetation cover demonstrated the best insulating effects. (6.2.2 & 6.2.3)

- In cooling load dominated regions, green walls have great potential in reducing the daytime energy loads and keeping the negative night-time insulating effects to a minimum. (6.3.2 & 6.4)

- In heating load dominated regions, insulation panels will be a better solution in reducing the energy loads. (6.3.2 & 6.4)

- The thermal effects of tested green wall systems were comparable, thus, choosing a system with low initial costs and maintenance requirements would be beneficial when focusing on the economical implication of energy load reduction. (6.4)

7. Environmental impacts of green wall irrigation

Green walls require constant maintenance in order to maintain healthy plants growth which has been proven vital in achieving optimal thermal benefits as well as retaining aesthetic values. As part of the experimentation described in Chapter 5, irrigation water consumption and excess water drained from each tested system were monitored to assess the prime environmental cost of green wall installation which could potentially offset the thermal benefits of vegetation discussed in the previous chapters. Following the introduction of issues concerning green wall irrigation in Section 7.1, types of irrigation system used in standard installation are explained in Section 7.2. The methodology of the experiments carried out for this study is introduced in Section 7.3, and the analysis of observation results are presented in Section 7.4. The key findings of the study are presented in Section 7.5.

7.1. Introduction

There have been concerns regarding the maintenance and environmental costs in order to keep green walls thriving, especially the requirements for mains water to irrigate a wall as both Takayama et al. (2014) and Natarajan et al. (2015) raised concern regarding the environmental and economic burden of green wall irrigation in their life-cycle cost analysis studies.

The results from the monitoring of foliage health within the test beds also emphasised the importance of providing appropriate maintenance in terms of irrigation and excess water drainage in the short period of twelve months. The figure below is an image of a hydroponic panel, showing some of the plants being distressed due to the failure of irrigation adjustments during the exceptionally dry weather in April 2013 with 9mm rainfall (historical average is 66mm). Plants in the hydroponic system were particularly vulnerable to droughts as they did not retain water as well as the other compost based systems.

Figure 7.1 A section of the hydroponic panel in April 2013, some types of plants became distressed as they were susceptible to droughts (2013)

The following figure shows the climber system twelve months after the installation which was originally part of the observed systems. Young climbers were planted upon installation and expected to provide foliage cover by the summer months. However, some of the plants died within a few months and the surviving species failed to establish in time. Over the observation period, the climber system was irrigated and fed to an identical schedule to that of the ivy screen next to the system, and it shared the volume of substrate. A few months into the experiment, the system stopped draining excess water due to a drainage pipe being clogged up with compost matter. This resulted in water and nutrients stagnating within the substrate severely affecting plant growth. The climber system was eventually omitted from the experiment. Similar failure of climber's foliage establishment was reported by Wong et al. (2010) which compromised results of their study that compared thermal impacts of green façades and living walls.

Figure 7.2 Climber system 12 months after the installation. Plants failed to establish and provide foliage cover (2013)

Another case of maintenance failure was observed in identical ivy screen panels to the tested system installed at Shef Square, a public space in front of Sheffield railway station. A large portion of plants on the screens died in less than twelve months of installation (Figure 7.4) due to an error in irrigation management (according to Hedera Screens Ltd, the supplier of the panels). Excessive irrigation caused water to overflow the container at the bottom of the plants, resulting in the roots of plants constantly sitting in stagnated water within the substrate. This eventually killed the majority of ivy plants which were later replaced.

The above cases illustrated the importance of the management of irrigation and drainage for green wall systems in order to maintain the aesthetical benefits of vegetation as well as to avoid unnecessary environmental and financial expense.

Figure 7.3 Ivy screens installed at Shef square shortly after the installation (April 2010)

Figure 7.4 Image of ivy screens at Shef square taken in February 2011

In this study, observation was conducted in order to seek a better understanding of the amount of irrigation water required by different green wall systems in order to sustain the growth of plants. The results were to provide good indications as to which system is the most efficient and also to explore future improvements on existing systems.

7.2. Living wall irrigation system

Early models of living walls required a vast amount of water in order to sustain plant growth, although the issue was raised in the industry and improvements have been made in some of the system designs to minimise water consumption for irrigation (Takayama et al., 2014). In general, felt based and hydroponic systems without conventional compost substrates require larger amounts of water as they do not retain moisture well within the system. All systems need to be fed with nutrients as they drain away with excess water over time. The excess water containing substances and nutrients rejected by plants normally drain away as waste and cannot be fed back into the system without a filtering process.

Green façades usually survive without irrigation supplied to the system, especially when the roots of climbers are directly planted into the ground or a sufficient volume of substrate is held within a container. Living wall systems on the other hand, require incorporated irrigation systems as their substrate volume is smaller and they can very quickly dry out. Living walls also have a vertical substrate layer covered with foliage which makes it difficult for rain water to permeate into the growing medium, as opposed to a horizontal substrate surface of green façades which collect rain water trailing down the climbers' foliage (Dunnett and Kingsbury, 2008).

The majority of living wall systems uses vertical drip line irrigation systems which consist of special pipes designed to apply water slowly through small emitters fitted inside the pipe at certain space intervals. The pipes are usually placed along the top of modular sections of a living wall to evenly distribute water which is driven around the system via an electric pump from a water tank. Irrigation is often managed by a controller which is connected to valves.

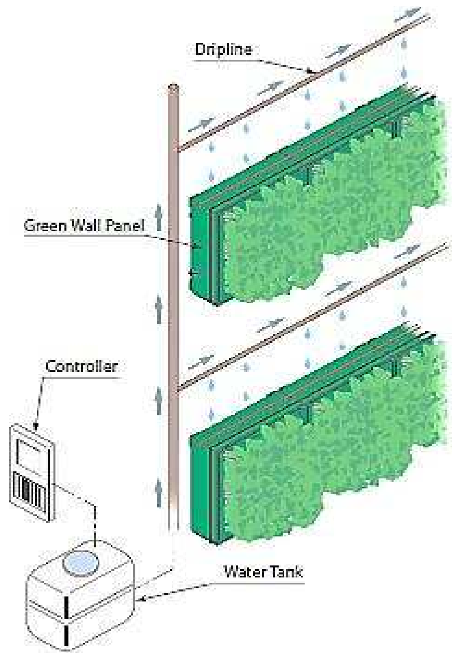


Figure 7.5 Schematic diagram of drip line irrigation system for green walls (Source: Gsky Plant SystemsInc, 2010)

Figure 7.6 shows the placement of irrigation pipes for the hydroponic and compost systems. In the case of both systems, drip line pipes are run along each row of living wall panel to distribute water evenly.

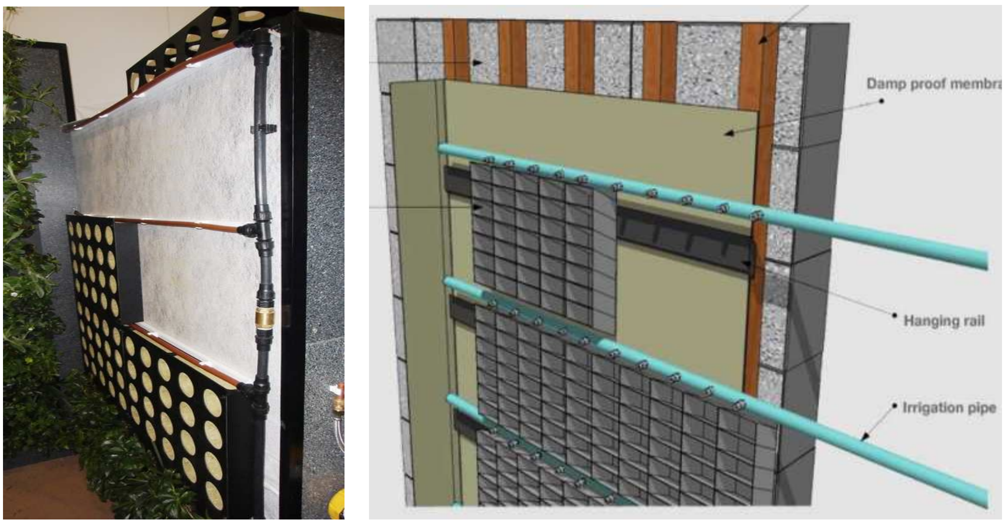


Figure 7.6 Irrigation pipe arrangement for the hydroponic (left, 2012) and the compost system (left, ScotscapeLtd, 2009)

The figure below shows a section of a felt based living wall system installed on the wall of a hotel in London. The system consists of two layers of felt fixed onto the building wall and the plants are inserted into slits made in the top layer of felt. The growing medium, in this case layers of felt, is not encased like other types of living wall systems, and is highly permeable. The entire wall needs to be constantly irrigated and fed through the pipes spread under the top layer of felt in order for plants to survive; this design causes the system to consume vast amount of water (Lambertini and Leenhardt, 2007).

Figure 7.7 Irrigation for the felt system, pipes and tubes are spread under the top layer of felt distributing water to the surface of the wall (2010)

7.3. Experimentation

7.3.1. Irrigation system of test beds

The figure below is a schematic diagram of the irrigation system for the green wall test beds. Mains water was supplied to a water tank with an electric pump inside it. Once water was pumped out of the tank, it was mixed with fertiliser and injected into the line. The main irrigation line was divided into secondary lines which distributed water and nutrition to separate sections of the wall. This particular zonal irrigation system is widely adopted within the industry of commercial living wall installations in order to apply appropriate amounts of water depending on the types of system or preference of particular species of plants.

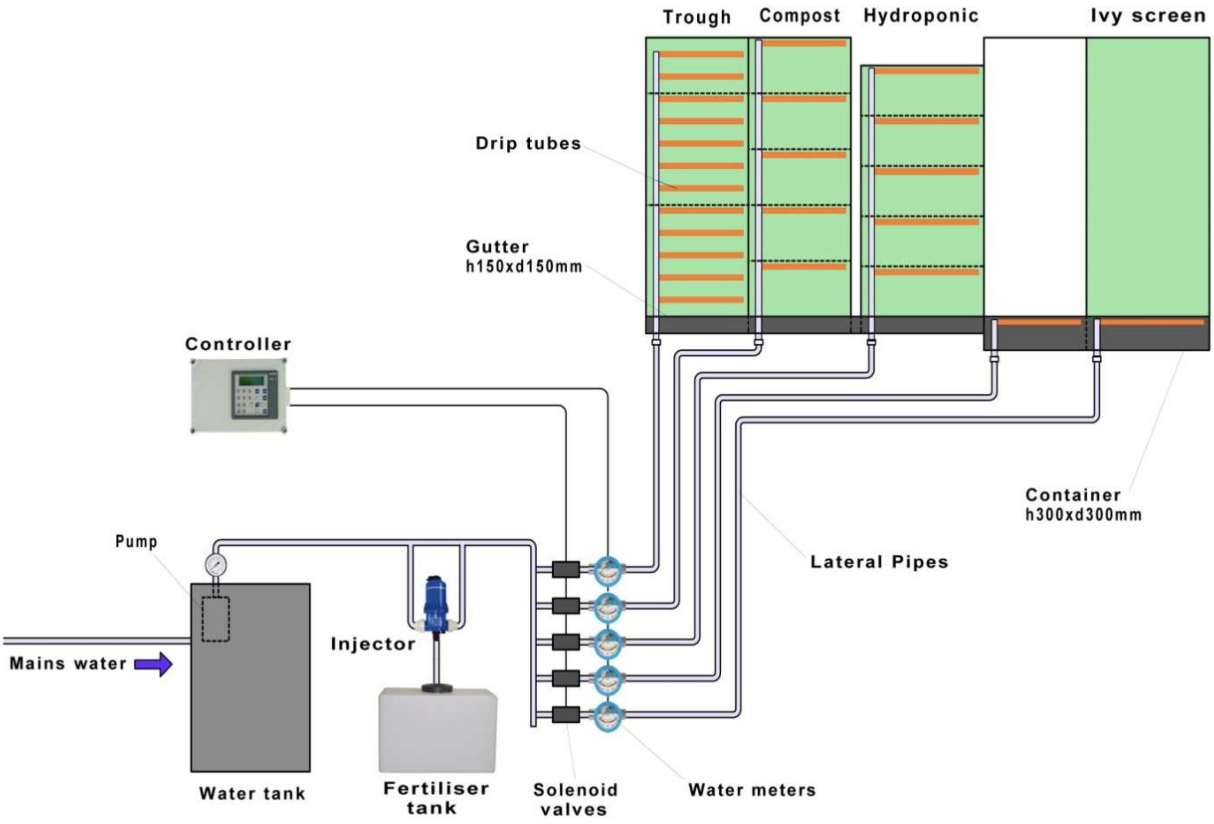


Figure 7.8 Schematic drawing of the irrigation system for the green wall test beds

The controller was programmed to apply different amounts of water to each zone. It activated a zone for a predetermined run time and at a predetermined start time; water was applied to the test beds when a solenoid valve opened automatically. Meters measured the amount of water supplied to each system and fed the information back to the controller. Five divided lines of irrigation pipes were connected to drip line irrigation pipes that horizontally ran across the systems. A line of drip irrigation pipes ran along the top of each compost and hydroponic panel, and into the planting container of the ivy screen system, feeding directly into the roots. The trough system was supplied with integrated drip lines laid along five rows of troughs that made up each panel. There were three different types of drip lines used for the test beds; each line had pre-fitted emitters at different spaces with a specific supply capacity (litres per hour) to apply water to meet irrigation requirements of a particular system. Irrigation rates were regulated by the drip lines regardless of the performance of the pump.

Table 7.1 Drip line pipes, spacing of emitters on the pipes and the supply capacity (litre per hour) of each emitter

System	Drip line	Emitter spacing	LPH per emitter
Compost	Custom Dripline	12.5cm	0.8
Hydroponic	Metzerplas Dripline	15cm	1.6
Trough	Techline	15cm	2.3
Ivy Screen	Metzerplas Dripline	15cm	1.6

The table below shows the initial irrigation schedule programmed into the controller panel upon installation, although in real terms it would be necessary to adjust the program throughout the life of the wall depending on the micro climate and weather including wind, precipitation and solar radiation rates.

Table 7.2 Irrigation program as of 6th November 2012*

System	Run Days	Start Time	Run Time
Hydroponic	Daily	13:00	3 min
Compost	Mon, Wed, Fri, Sun	14:00	4 min
Trough	Tue & Thu	15:00	4 min
Ivy Screen	Tue & Thu	15:00	12 min

* A proportion of the water would drain to the gutter, and therefore a calibration process would always be necessary to determine the exact irrigation requirements for the wall after installation.

During winter and early spring, the irrigation system is usually shutdown to prevent winter damage including stagnated water, frozen pipes and frozen substrates to the plants. For information of key components and the irrigation system of test beds, see Appendix E.

7.3.2. Irrigation and excess water monitoring of the test beds

The irrigation water supplied to each system was measured by separate flow meters and the readings were recorded to a controller. Daily readings were then sent out to registered email addresses at a predetermined time every day for remote monitoring.

Figure 7.9 Irrigation control and monitoring system of the test beds (2012)

Excess water from each panel of the living wall systems are designed to drain away from the back of the panel so that water discharge containing substances rejected by plants and the rich mixture of nutrients will not pass down to the panel below. The drained water travels down the surface of the water proof membrane behind the panels and into a gutter (See Figure 7.11). The drained water from the three living wall systems was collected by the gutter divided into three sections. This water then drained through separate pipes connected to excess water tanks located inside the building. Excess water from the two green façade systems was designed to drain directly through the pipes connected at the bottom of the containers and was also collected in tanks. The excess water collected was a mixture of excessive irrigation water combined with rainwater absorbed through the substrate that was not used by plants. The excess water collected in the tanks was measured and disposed of on a weekly basis. Each water excess tank could only hold a maximum of twelve litres and they often overflowed. Therefore, the maximum value of weekly measurements was twelve litres except for the trough system which had double tanks making the capacity twenty-four.

Figure 7.10 Water tanks to collect the excess water released from each test bed system. The trough system discharged more water than the others, thus it had double tanks (2012)

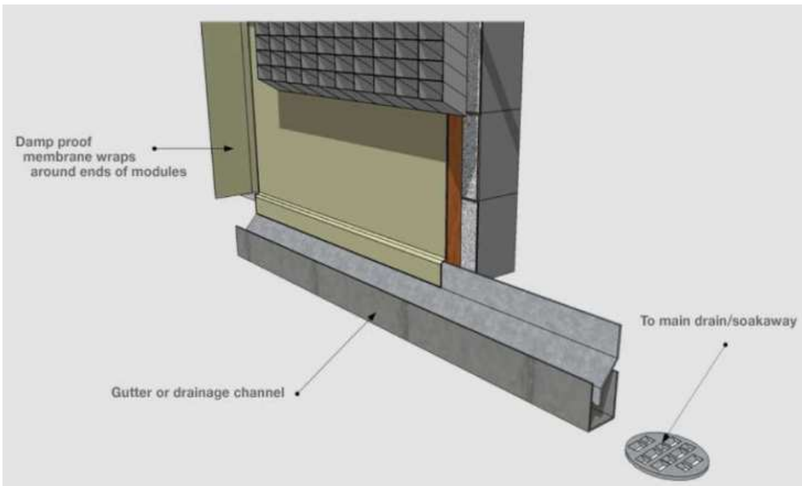


Figure 7.11 Schematic drawing of the drainage of a living wall system (ScotscapeLtd, 2009)

The calibration of irrigation and excess water monitoring was found to be challenging and it took the first four months of observation to obtain any viable data for analysis. There were a number of factors that contributed to the delay, including too much water applied to the systems at the beginning of the study. Between January and April, the irrigation rate was lowered to a minimum level in order to avoid winter damage to plants such as water-logged substrate. During this period, the excess water tanks for the living wall systems often flooded and it was discovered that the gutters were collecting rainwater falling into the gap between the surface of the wall panels and the edge of the gutter. The excess water monitoring finally commenced in mid-April 2013 after the issue was eventually solved by stapling the opening using a sheet of waterproof membrane as a cover.

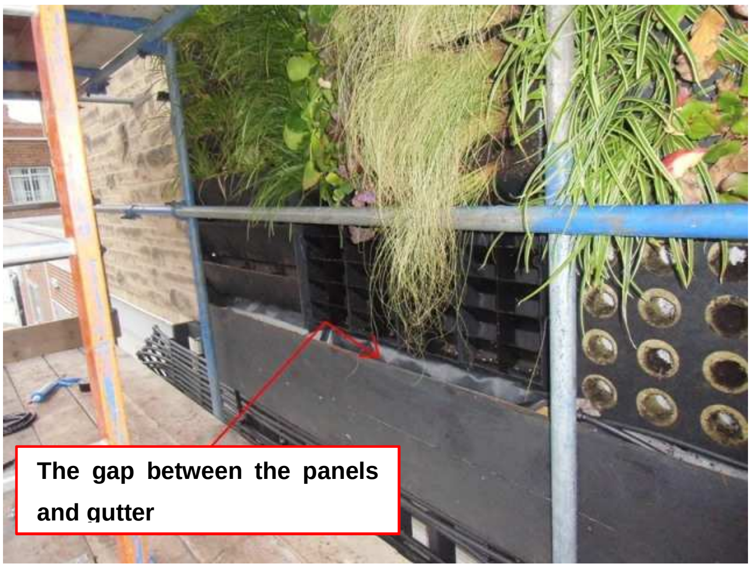


Figure 7.12 Image of the bottom of test beds before covering the gap between the living wall panels and the gutter (2012)

7.4. Results and discussion

Analysis was carried out on irrigation and excess water data collected in a twelve-month monitoring period between December 2012 and November 2013. This was to investigate the amount of water consumed by three variations of living wall systems and a green façade panel and the potential improvements that could be made to the existing irrigation regimes to reduce the environmental cost of green wall maintenance. The observation results of each system were compared to each other and against the rainfall data to look at the possibility of the usage of reclaimed water for irrigation. Since there was a problem with the drainage and plants' growth of the climber system, the data from this system was excluded from this analysis.

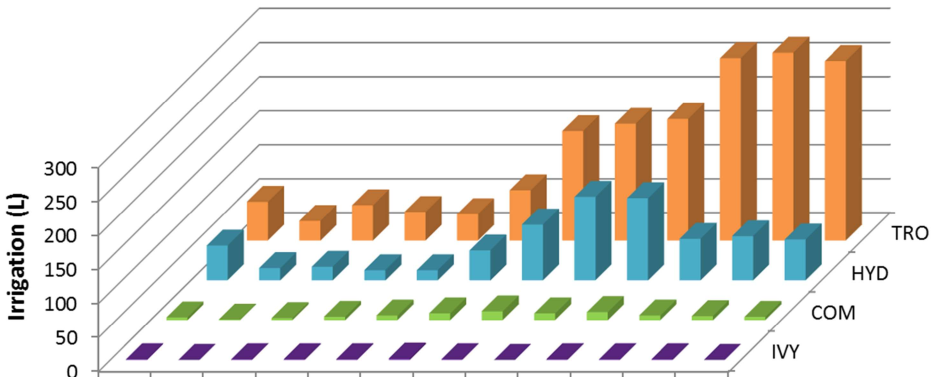
7.4.1. Water consumption for irrigation

The remote monitoring system of test bed irrigation was occasionally affected by communication system errors within the controller panel, and some readings of irrigation water flow were not recorded. However, absent readings remained approximately two per month on average throughout the observation period, and this data was calculated by using before and after average readings for the purpose of analysis.

The following figure shows the total amount of irrigation water provided to the four separate test beds. The results indicate that throughout a year, the trough and hydroponic systems required more water compared to the compost system and ivy screen that thrived regardless with very little irrigation. All four systems provided sufficient coverage of foliage and maintained the aesthetic benefits of green walls. The result of the irrigation supply study outlines the fact that the compost system and ivy screen are most efficient in retaining and utilising irrigation water to sustain plants' lives.

The irrigation rate was turned down during the winter period to avoid damage to the roots of plants. It was gradually increased towards the height of summer when plants require larger amounts of water to develop in spring time and to survive in hot weather.

It should also be noted that the Trough system was over watered between September and November. This was again due to the failure of irrigation management and it is expected that the system require less water in standard installation.



	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
IVY	1	0	1	1	1	2	1	0	1	1	1	0
COM	4	1	3	5	7	10	13	10	12	7	6	5
HYD	51	18	20	15	15	44	82	123	121	61	65	60
TRO	57	29	52	42	39	74	161	172	179	268	276	264

Figure 7.13 Irrigation water (Litres) provided to respective test beds in each month

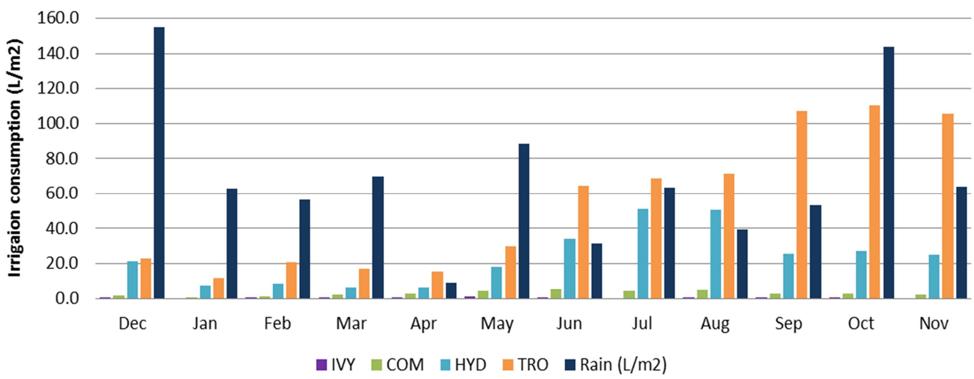


Figure 7.14 Total monthly irrigation water supplied to four green wall systems compared to the recorded monthly rainfall (1mm of rainfall=1Litre of water/m^2)

The figure above shows the comparison of irrigation water supplied to a square meter of the respective systems and the recorded rainfall (also in litres per square meter) in each month. As will be explained in the next paragraph, excessive water supplied to the systems simply drained away, therefor the trough and hydroponic systems might not have required as much water as was provided to them during the study. Even if they did, the graph indicates the monthly rainfall exceeded the required amount of water for each test bed except for the trough system.

The table below shows the recorded total rainfall and irrigation water consumption during the twelve month period of observation. It suggests there is great potential in the utilisation of cultivated water to irrigate living walls by incorporating rain water harvesting systems in places which have a sufficient annual precipitation rate such as the city of Sheffield, UK.

Table 7.3 Total rain water fallen in Sheffield and recorded irrigation water consumption for each system during the twelve month observation period (Litre/m^2)

Rain water	Compost	Hydroponic	Trough	Ivy screen
836.8	42	338	807	5

7.4.2. Excess water

The analysis was conducted on the data collected in the eight month period between April and November 2013 using Microsoft Excel.

The table below shows the total amount of irrigation water consumed and the excess water released from the four tested systems. The capacity of the excess water tanks was limited and the water discharge often exceeded the tank capacity of twenty-four litres (Trough) and twelve litres (others). Despite the limitations of acquiring accurate data, the table demonstrates that the total amount of excess water from the compost system and ivy screen surpassed the amount of water supplied to the system. This result suggests the substrates managed the absorption process and release of rainwater in a more efficient manner. On the other hand, the two living wall systems, hydroponic and trough were supplied with eight to twenty times more water compared to the compost system, and a large proportion of the irrigation water combined with rainwater absorbed by the substrate drained away from the system. This assumption is based on the table showing those two systems released about 40% of the water entering the test beds, and as previously stated this proportion would have been much larger had it not been for the limited capacity of excess water tanks.

Table 7.4 Total irrigation and excess water for each system in eight months (Litre/m^2)

	Compost	Hydroponic	Trough	Ivy screen
Total irrigation water (L)	35	286	717	4
Total excess water (L)*	131	109	241	60

* Maximum values are 12 litres per week except the trough system which was 24 litres per week

Compost system:

The figure below shows the weekly records of irrigation, excess water and the rainfall of the compost system during the period from 11th April to 26th November. Throughout this period, there were never more than three litres of water per week supplied to the compost test bed measuring a meter wide and 2.5 meters high. The amount of excess water exceeded the total supply of irrigation water most of the time and it was recorded at the maximum value of twelve litres almost every week from the 8th of August.

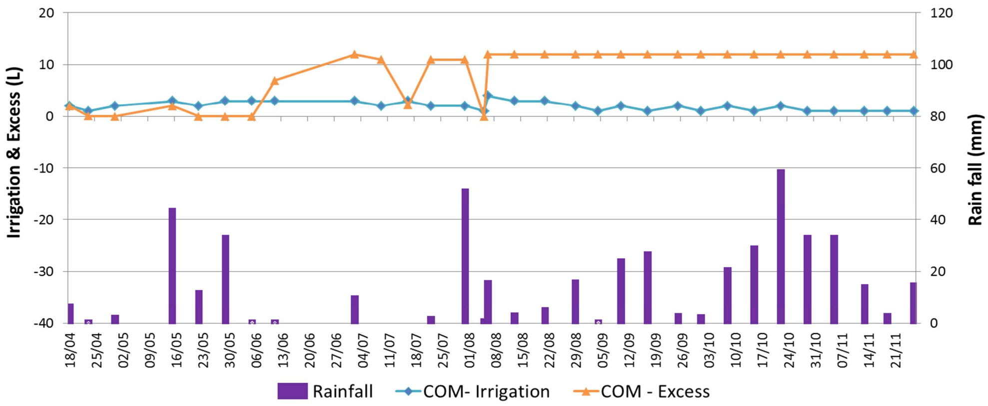


Figure 7.15 Weekly Irrigation and excess water that entered into and was released from the compost system test bed

The following two figures show that the system released more water than the irrigation system supplied and there was no coherence in the relation of both readings, hence, the data points are scattered around on the graph and the coefficient between the excess and irrigation water is in minus. Figure 7.17 suggests that the excess water discharge had slightly better correlation to the rainfall. Excess runoff readings from the compost system showed the least correlation to neither two variables compared to the other systems, indicating that the system retained water within the substrate and delayed in releasing the excess.

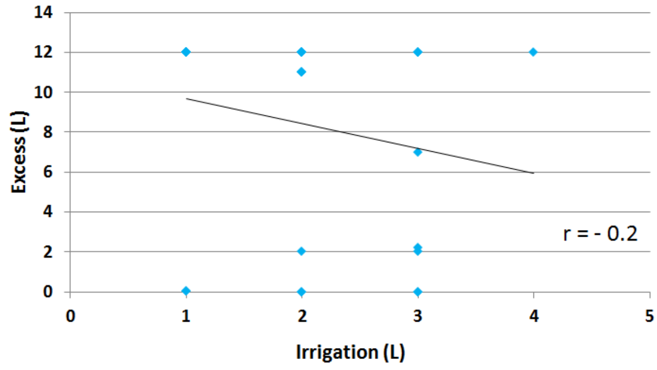


Figure 7.16 Correlation of excess water discharge against irrigation supply (Compost system)

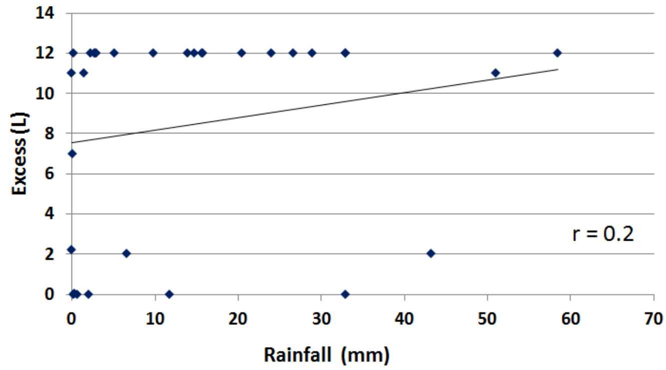


Figure 7.17 Correlation of excess water discharge against rainfall (Compost system)

Hydroponic system:

The following figure shows that throughout the period shown, the amount of water that the system consumed exceeded the total of drained excess water. The irrigation consumption was especially high in July and August. The maximum value of excess water (twelve litres) was recorded every week after the 10th of October when there was consistent rainfall, suggesting that the irrigation could have been turned down during this period.

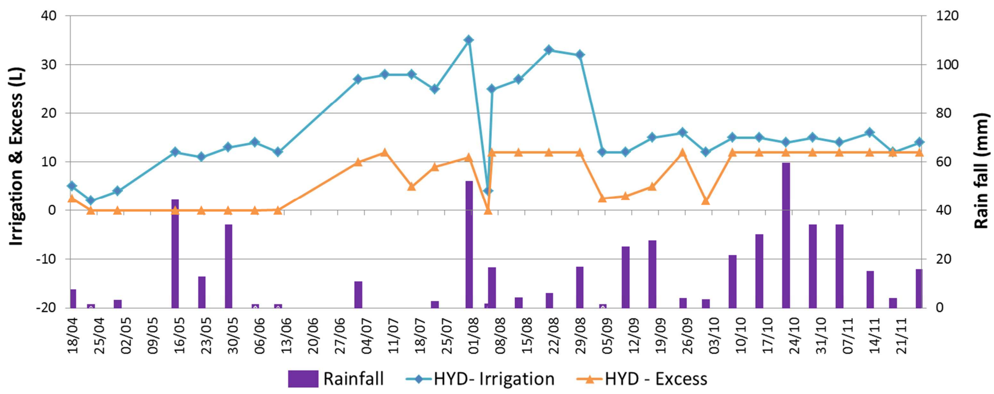


Figure 7.18 Weekly Irrigation and excess water that entered into and was released from the hydroponic system test bed

The correlation of excess water discharge against the irrigation supply was significantly higher than against the rainfall, indicating that a large proportion of irrigation water went straight through the substrate and drained away. The lack of ability to retain water within this type of system increases the requirement of irrigation in order to keep plants' roots in contact with water.

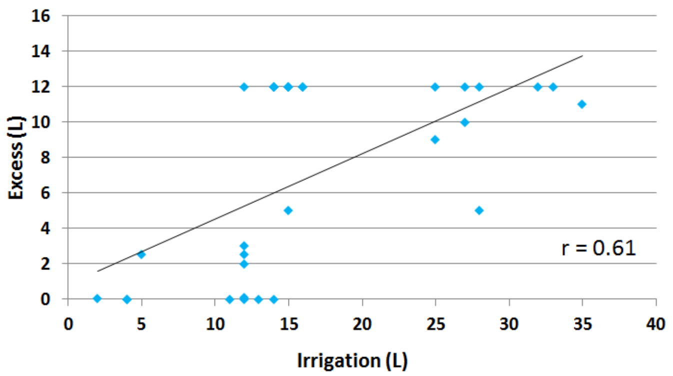


Figure 7.19 Correlation of excess water discharge against irrigation supply (Hydroponic system)

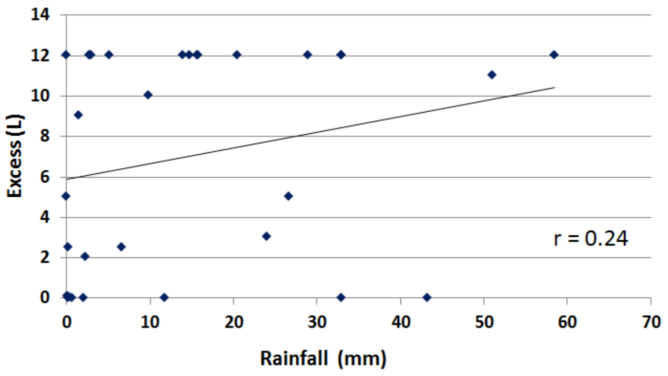


Figure 7.20 Correlation of excess water discharge against rainfall (Hydroponic system)

Trough system:

The trough system was supplied with much larger amounts of water during the observation period compared to other systems and consequently, released large amounts of excess water. The following weekly irrigation and excess water graph shows the amount of water that the system consumed exceeded the total of drained excess water throughout the period. After the 29th August, 24 litre tanks were often found to be heavily overflowing when high rainfall as well as irrigation rates were recorded.

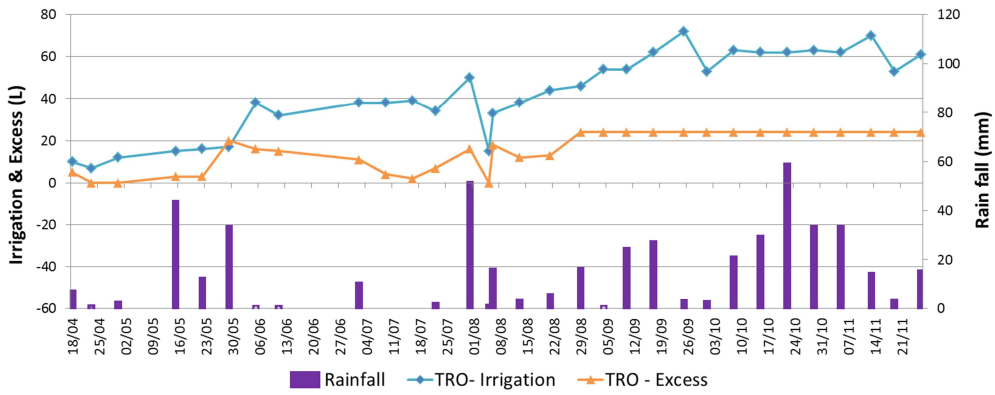


Figure 7.21 Weekly Irrigation and excess water that entered into and was released from the trough system test bed

The following correlation graphs outline that the amount of excess water discharged from the trough system was undeniably related to the amount of water supplied to it. As the substrate of the trough test bed was identical to that of the compost test bed, it had the same or possibly better water retaining capacity considering the fact that the modular components of trough system were designed to hold a larger volume of substrate. This extremely high correlation indicates the system was over irrigated for the entire period resulting in a permanently saturated substrate and the majority of irrigation water drained away without being utilised by the plants.

The amount of excess water released from the trough test bed was also correlated to the rainfall record, and the degree of correlation was much more prominent than the other two living wall systems. The difference in the results could be related to the design of each system's modular units. While both compost and hydroponic panels have vertical openings for plants to be inserted, the trough unit has horizontal openings and plants grow upright in a more natural way. This design makes the trough unit capture rainwater more easily and the results furthermore suggest the possibility that the trough system requires much less irrigation than the total water consumption recorded in this study.

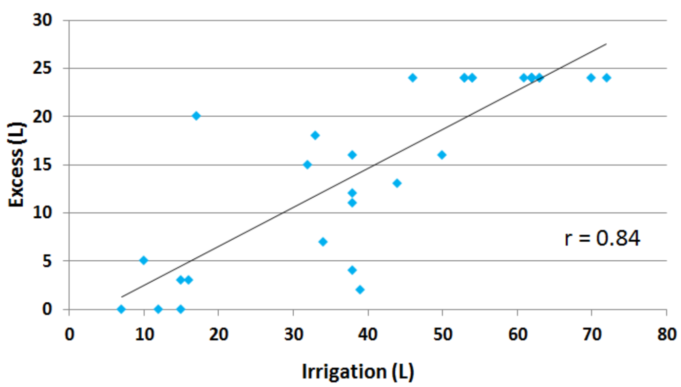


Figure 7.22 Correlation of excess water discharge against irrigation supply (Trough system)

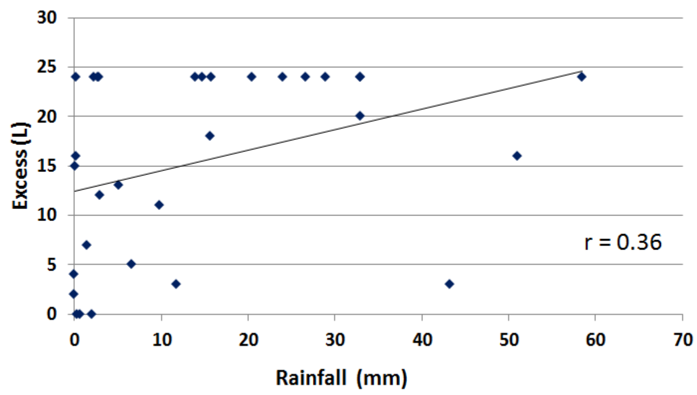


Figure 7.23 Correlation of excess water discharge against rainfall (Trough system)

Ivy screen:

Throughout the observation period, ivy screen was rarely irrigated. The figure below shows that irrigation and rain water provided to the system was absorbed and used by plants during the dry period and the excessive rainwater drained away once the container filled substrate was saturated.

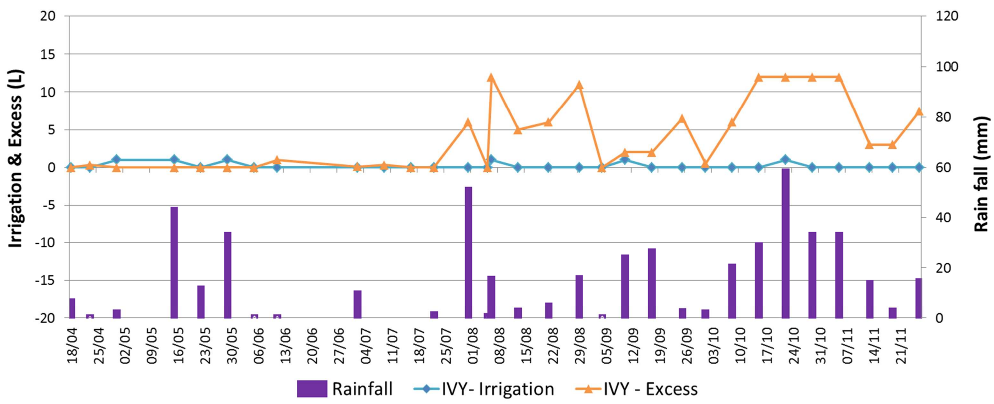


Figure 7.24 Weekly Irrigation and excess water that entered into and was released from the ivy screen test bed

There was no correlation between the discharge and irrigation as the ivy screen test bed was rarely irrigated throughout the experiment. On the contrary, Figure 7.26 shows a distinct correlation between the amount of excess water and rainfall. Both Figure 7.24 above and the moderate level of coefficient indicate a delay in the system discharging the excess water after rainfall, demonstrating the capacity of the substrate mass to absorb and retain rainwater. The results suggest that in places where it has consistent and sufficient precipitation throughout the year, ivy screen will not require any integrated irrigation system providing there is enough depth in the substrate to retain adequate moisture levels.

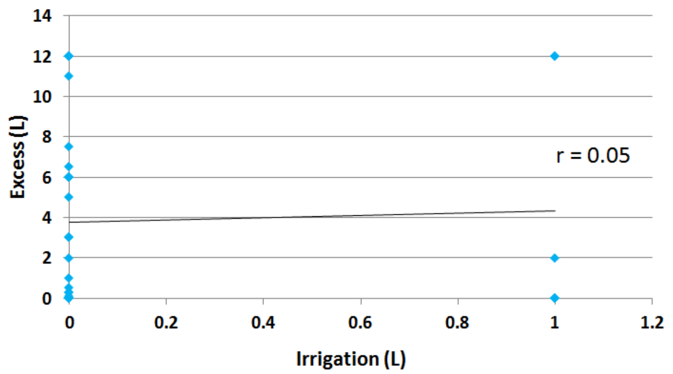


Figure 7.25 Correlation of excess water discharge against irrigation supply (Ivy screen)

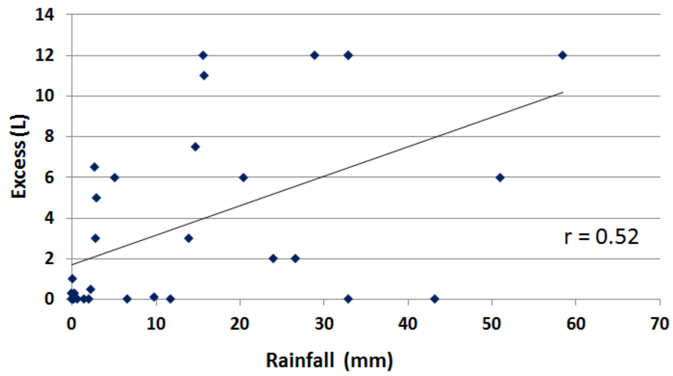
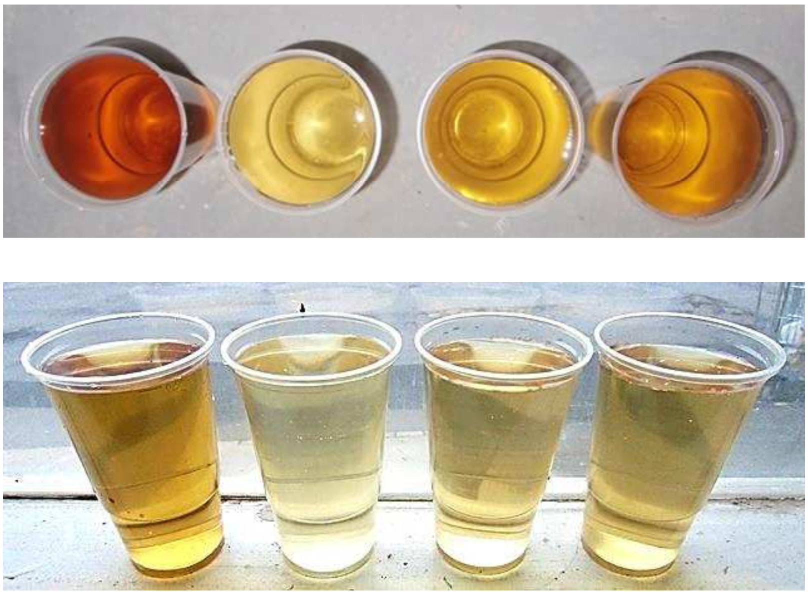


Figure 7.26 Correlation of excess water discharge against rainfall (Ivy screen)

7.4.3. The quality of discharged water

There is currently much debate within the industry regarding the prospect of adopting loop cycle systems into green wall irrigation in order to utilise excess water released from the system by recycling the discharged water back into the irrigation cycle. In this study, the quality of collected excess water was not looked at in detail, although the images of drained water from the different systems suggest that the quality might differ depending on the system. Any excess water released from the system would require a filtering process to remove harmful substances reaching the plants before being fed back into the loop. Further studies will be necessary to investigate the feasibility, economic and environmental issues of such applications.



Ivy screen   Hydroponic   Compost   Trough

Figure 7.27 Image of excess water released from the four tested systems.

7.5. Conclusion

This chapter explained the field experimentation and results of the analysis using data collected in order to assess the irrigation water required by different green wall systems and efficiency of tested systems in utilising irrigation water. The main findings of these studies are as follows.

- Irrigation water consumption of green walls during the twelve month period varied greatly between 5–807 litres/m^2, partially due to the mismanagement of automated irrigation system resulting in large quantity of water simply drained away from the vegetation. (7.4.1)

- The compost system was most efficient in utilising irrigation water among the tested living wall systems as the system retained water well within the substrate and delayed in releasing the excess. (7.4.2)

- A large proportion of irrigation water supplied to the Hydroponic test bed simply drained away. The lack of ability to retain water within the system increased the requirement of irrigation. (7.4.2)

- The trough system was supplied with much larger amounts of water compared to other systems. As the trough unit had horizontal openings which made it easy to capture rainwater, it would have required much less water than was introduced to it. (7.4.2)

- Ivy screen would not require any integrated irrigation system in places where consistent and sufficient precipitation occurs throughout the year. The large container at the bottom of the screen made it easy to collect rainwater, and the substrate mass retained large amounts of water delaying runoff discharge. (7.4.2)

- Utilising cultivated water to irrigate vegetation by incorporating a rain water harvesting system would reduce the environmental impact of living wall maintenance in places which have sufficient annual precipitation rates. (7.4.1)

8. Conclusions and future work

8.1. Findings from the studies

This study investigated the thermal effects of green roofs and walls on buildings throughout four seasons within the UK climate. Field studies and thermal analysis were carried out to investigate the impacts of vegetation on building surface temperatures, indoor air temperature, heat flow through the envelope and energy loads for heating and cooling. It also briefly explored the potential environmental impacts of green wall irrigation.

The conclusions corresponding to the research objectives described in Section 1.2 are as follows.

1) The effects of green roofs and walls on the thermal performance of buildings throughout four seasons in the UK

Roof surface temperatures:

Roof surface temperature data was collected during a 31-month field experiment utilising a green roof which consisted of varying depths of substrate. Results showed that vegetation layers minimised the influence of the elements and regulated the roof surface temperatures throughout the day regardless of season. The surface temperature of the exposed roof fluctuated as it was influenced by solar radiation during the day and cooler temperatures at night, frequently reaching over 50℃ in the afternoon on clear summer days. On average, the green roof reduced daily peak temperatures of the roof surface by approximately 12℃ in the warmest month. This reduction was slightly lower than previous studies as most were conducted in climates experiencing much higher temperatures and increased solar radiation exposure in summer compared to Meltham, UK (where this experiment was carried out). Vegetation also delayed peak temperature times by two to six hours by slowing radiation heat from reaching the roof surface. The effect was more significant in the green roof with a thicker substrate, being in line with data from existing studies.

Green roofs were proven to be more effective in reducing surface temperatures in summer than increasing them in winter as they only increased the minimum roof surface temperatures by 0.9–1.8℃ during the winter months. The observation results also indicated a potentially undesirable effect with a vegetation cover. The green roof increased the mean daily minimum temperature for the warmest month by 2.4–5℃, which could become a factor that would adversely reduce radiating heat released through the roof in regions with a high energy demand for cooling at night. The green roof also decreased daily peak temperatures of the roof surface in winter by an average of 5.5℃. The cooler external surface can increase heat loss through the roof and consequently energy loads for heating in buildings with high daytime occupancy such as offices and educational buildings in regions where demand is predominantly for heating.

External wall surface temperatures:

Results of a twelve-month experiment conducted using green wall test beds installed on the southwest facing wall of a building in Sheffield, UK, demonstrated that the impacts of a vegetation layer on external wall surface temperatures were similar to that on the roof surface. The green walls regulated the external wall surface temperatures behind the vegetation and reduced daily temperature fluctuations occurring on the exposed wall surface throughout the year. They were particularly effective in reducing daytime temperatures in summer, decreasing the average daily peak by 12.1℃ during the warmest and brightest month when the peak temperature of the reference wall surface averaged 35.5℃, echoing previous findings in a subtropical climate. The degree of the green walls' impact was strongly linked to the level of solar radiation and outdoor air temperature, meaning reductions were more substantial in spring and summer. However, insulating effects of the green walls were less significant; they increased the average daily minimum temperature of the external wall surface by 2.8℃ in the months when the minimum outdoor temperature was below 5℃. These observational results clearly suggest that green walls are more effective in mitigating the influence of solar radiation, decreasing external wall surface temperatures in warm weather and more so than increasing surface temperatures in cold weather. As was found in the green roof study, the impacts of green walls on external wall surface temperatures were not always favourable. In the spring and summer months, vegetation cover increased the average daily minimum temperatures by 1.8℃ at night. Although the impact appeared negligible in this study, a warmer external surface in summer could potentially increase the night-time heat gain through the wall in warmer regions than the UK. Vegetation also decreased the average maximum temperature by 3.7℃ in the autumn and winter months while the reference wall surface gained heat from solar radiation. A post experiment numerical study found that the cooler building exterior surface in cold seasons resulted in an increase in daytime heat loss through the wall.

Internal surface and indoor air temperature (green roof):

Measurements taken for ambient air temperature readings by loggers attached to the ceiling under the green roofs showed only marginal differences to that under the roof without vegetation cover. This was due to the 100mm insulation layer (U-value: 0.22W/m^2/K) within the original roof construction minimising the impacts of green roofs. The result validated existing reports stating that the effects of vegetation become negligible on highly insulated roofs. Although the actual effects on internal temperatures were insignificant, green roofs increased the ambient temperature near to the ceiling by 0.2–0.4℃ throughout the year by marginally increasing thermal resistance and reducing heat released through the roof structure.

Internal surface and indoor air temperature (green wall):

Internal wall surface and indoor air temperatures were measured inside a room of which the southwest facing external wall was covered by green wall test beds, where recorded temperatures were compared to corresponding measurements taken inside the reference room directly above. Observation results revealed that the impacts on the external wall surface were reflected on the internal temperatures of the building. The internal surface temperature of the reference wall peaked between 20:00 and midnight throughout the year due to solar radiation transmitted onto the exposed exterior surface during the day and was then stored within the structure and emitted towards the internal space at night. The same time delay was observed for the indoor air temperature next to the reference wall. Since green walls minimised the influence of solar radiation and regulated the temperature of the external wall surface throughout a day, the internal wall surface temperature did not show the effects of outdoor weather and there were no temperature increases observed during the night. During the summer months, the green wall systems reduced both daily peak and minimum temperatures of the internal wall surface by 1.5℃ and 1.3℃, respectively; the figures were consistent with the findings of other studies. During the winter months, green walls increased both daily peak and minimum temperatures by 1.7℃ and 2.1℃.

The effects of green walls on the internal wall surface were then reflected on the indoor air temperature next to the wall. Green walls increased the indoor air temperature throughout the year except for the summer months. They increased the indoor air temperature near to the wall by 2.3℃ in winter and decreased it by 1℃ in summer; the effects became less significant further away from the wall and those figures became less than half of that quoted in the centre of the room. The indoor temperature increase in winter was larger than the reduction in summer due to the current climate of Sheffield. The reduction in indoor air temperature near to the wall for the brightest and warmest month during the observation period was 1.5℃ on average, nearly double the results of the other two summer months, suggesting that green walls would show a more significant impact in reducing indoor air temperatures in warmer climates than the UK.

Heat flow through the wall:

The amount of heat gained and lost through the original wall structure during the twelve-month period was calculated based on the temperature difference between external and internal wall surfaces using temperature data collected during the field experiment.

Results of the numerical analysis demonstrated that green walls were more effective in reducing diurnal heat gain through the wall than heat loss. Green walls minimised solar radiation gain throughout a year and reduced over 99% of daily mean heat gain in spring and summer. They also increased daytime heat loss through the wall by keeping the exterior wall surface cooler than the interior surface and consequently eliminated annual air-conditioning loads during the study period. However, the same effect resulted in a 1–6% increase in the daily mean heat loss in cold periods.

Vegetation cover provided insulation during the night, decreasing the amount of heat escaping through the wall, although the impacts on the autumn and winter heating loads were diminished as night-time heat loss reductions of 12–17% were offset by an undesirable daytime heat gain reduction of 6–9%. During the hottest month, this insulating effect also adversely decreased night-time heat loss through the wall, which could lead to higher air-conditioning loads in warmer regions compared to Sheffield.

2) Factors that influence the thermal performance of green roofs and walls

The thickness of green roof substrate:

Comparison of indoor air temperatures under the green roofs of varying substrate depth indicated that the thickness of the substrate influenced thermal performance of the vegetation layer. The 300mm and 400mm green roofs increased the indoor air temperature in all seasons while the 120mm green roof provided similar insulating benefits in winter without significant temperature increases in summer. During the hottest month of the observation period, the 300mm and 400mm green roofs increased the indoor air temperature by 0.6℃ compared to the non-vegetated and the 120mm green roof sections. These results along with previous findings of 100–150mm green roofs reducing internal temperatures under the vegetation in warm climates indicate that an increase in the thickness of growing medium could result in increased insulating properties due to greater thermal resistance, providing unwelcome effects in summer increasing the air temperature under the roof. This suggests that from the perspective of thermal benefits, extensive and semi-intensive green roofs (substrate depths of 80–200mm) would provide similar thermal benefits in increasing the indoor air temperature in winter and a less negative insulating impact during summer in warmer climates. Intensive green roofs (substrate over 200mm) with greater thermal resistance would be suitable in places with cooler climates to provide insulating effects throughout all four seasons.

Type of wall greening systems:

In terms of impacts on the wall surface temperatures, heat flow through the wall and building energy loads, only a marginal difference was observed amongst all tested green walls including three modular living wall systems and a climber screen unit. With regards to insulating effects, a living wall system with a large volume of substrate, such as Trough system showed marginally increased thermal resistance and better performance in increasing minimum temperatures of the external wall surface by around 0.5℃ compared to the others in all seasons. The Ivy screen without a substrate layer had a marginally less impact on heat loss reduction. In warmer months, all tested green walls provided comparable effects in reducing heat gain through the wall. Hence, choosing a system with the lowest initial installation costs and subsequent maintenance would be beneficial from an economics perspective. This validates the conclusion of an existing life-cycle cost analysis study.

Presence of plants in green walls:

Measurements taken from test bed sections where each living wall system had modules without plants and the Ivy screen had an area with little foliage cover revealed that plants did not provide additional surface temperature reductions in summer; however, they were found to be an important factor in increasing the insulation performance of green walls in the autumn and winter months. When absent, the minimum temperatures of the external wall surface decreased by 1.5℃ and the internal surface by 0.2℃ on average, which resulted in an 8% increase in heat loss through the wall compared to the systems with plants. This demonstrates that maintaining sufficient foliage cover is essential in optimising the insulating performance of a vegetation system during cold weather.

Added insulation layer to provide further thermal effects:

As expected, results from the tested green wall units with 100mm insulation board (λ=0.022W/mK) inserted in the gap between the back of the vegetation and the building wall showed improved thermal resistance to existing green wall systems. It increased both daily peak and minimum temperatures of the external wall surface by 1.3℃ and the minimum temperature of the internal surface by 0.7℃ compared to the original systems in the autumn and winter months, resulting in an 11% reduction in heat loss through the wall (against original systems). Thus, adding insulation to existing green wall systems would be beneficial in climates with high heating energy demands. It should be noted, however, that this recommendation is only applicable in the case where green walls are installed for the purposes of providing multi-functional benefits such as ecological and social in addition to thermal benefits in cold climates, as conventional insulation material appears to be a better solution in simply improving the insulating performance of a wall as explained in the section below.

Also, the increased insulating properties can have an adverse impact, particularly on night-time cooling loads in summer due to the reduced amount of heat lost through the wall. Hence, combining a vegetation system with insulation material would not be an appropriate solution in improving a wall's year-round performance where air-conditioning loads are a significant factor.

3) The effectiveness of green wall systems as a building insulation material in the UK climate

Potential energy savings:

A potential reduction in energy requirements for heating and air-conditioning as a result of green wall installation was determined based on heat exchange through the wall by using recorded temperatures during the field experiment. Green walls reduced a larger amount of energy load for cooling than heating despite the fact that the cooling load accounted for less than 10% of the total annual energy loads of the observed wall. This further highlights the true potential of green walls being best utilised in climates where air-conditioning loads are a dominant factor. The ability of green walls to minimise radiation gain and increase heat loss during the day had an adverse effect on daytime heating loads in cold weather. Even though vegetation cover decreased the heating load due to heat loss through the wall during the night, the effect was offset by the increase in daytime heating load in winter. This means the potential economic benefit of green walls will be minimal in climates where building energy consumption is primarily for heating as found in other studies conducted in the temperate and continental climates.

Performance compared to conventional insulation materials:

The comparison between the performance of a 100mm insulation panel (λ=0.022W/mK) and green wall systems revealed that the external insulation was actually more effective in reducing heat loss through the wall behind it. Whilst the insulation board reduced heat loss by 25% between October and March, the green walls with an insulation panel only reduced it by 5–11% and the original systems adversely increased it by 1–6%. This suggests that vegetation systems may not provide additional insulating benefits to an external insulation material and may also decrease performance of externally pre-insulated walls. Thus, a conventional insulation material, which is considerably simpler and economical to install and maintain, would be a better solution in improving performance of a wall in climates where heating loads are a dominant factor. The true potential of green walls lies in its variable characteristics as an insulation material which reduce radiation gain during the day with less effects in inhibiting heat released through the wall at night compared to conventional insulation materials. As a number of previous studies have concluded, the greatest thermal benefits of green walls can be attained in cooling load dominated regions.

Environmental impacts of green wall irrigation:

As part of the field experiment, irrigation water consumption and excess drain off from each tested system were monitored to assess the prime environmental costs of green wall installation which could potentially offset the thermal benefits of installing vegetation. Irrigation consumption during the twelve month period varied greatly between 5–807 litres/m^2 depending on the system, this was partly due to the initial mismanagement of an automated system resulting in excessive irrigation. This highlighted the importance of consistent monitoring and control of irrigation to minimise overall consumption for green wall maintenance. Utilising cultivated water to irrigate vegetation by incorporating a rain water harvesting system would help reduce the environmental impact in places which have sufficient annual precipitation. In general, compost based living walls were found to be more efficient in utilising irrigation water compared to hydroponic systems which lack the ability to retain water within the growing medium. The large open top container at the bottom of the Ivy screen made it easy to capture rainwater and the substrate mass helped retain it. This system would not require any integrated irrigation system in geographical areas where consistent and sufficient precipitation occurs throughout the year.

8.2. Recommendations for further research

The true benefits of vegetation as a building insulation material are highlighted by their ability to thermally adapt and provide evaporative cooling and insulating effects simultaneously within a constantly changing outdoor climate. The green roof study revealed that installing ever thicker substrate layers does not necessarily increase the thermal benefits in certain climates as either of these effects can become unfavourable depending on the internal thermal conditions of a building. This suggests that there is an ‘optimal’ thickness for any given green roof layer in order to provide an optimum balance of benefits within specific climatic conditions. Since both evaporative cooling and insulating effects are dependent on the thermal conductivity and moisture level of the substrate (Sailor et al., 2008), exploring the influence of substrate mass within these parameters in a controlled environment would be beneficial to help optimise and to gain a better understanding of the thermal benefits of green roofs in the future.

Although results of the field observations were case sensitive and the details only applicable to the observed buildings in the UK climate, the present research provided physically measured quantitative data, which can be utilised in the validation of simulation models in the future. There have been many discussions and attempts to determine U-values of green roofs and walls in order to compare insulation performance against conventional building materials. However, this has proved challenging as the heat transfer within a vegetation layer is not precisely linear, or only conductive in nature. The insulation properties of vegetation are influenced by numerous factors and in particular, the variable moisture level within the substrate which depends on both local weather and climatic conditions. For those reasons, green roofs and walls are currently not provided a U-value (Groundwork Sheffield, 2012). Thus, development of an accurate theoretical model which can incorporate a complex and variable energy balance for vegetation is vitally important in order to establish ways to evaluate the thermal impacts on a project-by-project basis. Since the thermal effects of vegetation cover consist of many variables due to their organic make up (i.e. substrate and plant type etc.), exploring the thermal characteristics of these components in a controlled study would also help to improve the accuracy of a theoretical model for green walls.

Existing simulation studies suggest the orientation of a green wall to be a key influential factor in the thermal impacts of vegetation; the subject could be explored further using field measurements to validate such findings.

This study found the insulating performance of green walls decreased in cold and windy weather conditions, contradicting previous assumptions that a vegetation layer acts as a wind barrier. Jim and Peng (2012) also highlighted the association of wind speed with cooler surface temperatures on green roofs in a tropical climate, which further suggests an increased evapotranspiration rate and decreased thermal resistance due to air flow. The subject requires further investigation in relation to both the cooling and insulating effects of green roofs and walls.

The focus of this study was on the thermal impacts of vegetated envelopes on an individual building and the results demonstrated minimal benefits in climates such as the UK. It is, however, important to note that this did not take account of collective thermal benefits that urban vegetation can provide on a city scale. Significant impacts of vegetation cover on external surface temperatures of buildings were evident in the field measurements of both green roofs and walls. Vegetation on hard building surfaces can reduce the amount of heat absorbed in the external structure of a building being released back as long-wave radiation causing the ambient air temperature to rise. The effects are already a serious environmental issue in warmer parts of the world and are predicted to become a much greater concern in the future within urban areas of the UK

(Norton et al., 2015). Thus, the potential benefits, such as mitigation of the Urban Heat Island effect should be included in the discussion of the thermal impacts of vegetated envelopes and explored further with a great emphasis and consideration given to the effects of global warming.

The investigation into irrigation management within this thesis was elementary at best and the limitations of the excess water tanks' capacity compromised the accuracy of measurements. Existing knowledge on water consumption and runoff is limited, particularly on green walls (Takayama et al., 2014). Real time run off monitoring would provide a more detailed understanding of the correlation between irrigation, rainfall and excess run off with a view to investigating the potential application of green walls within storm water management. Excess water quality would also be a beneficial area of study with prospects for achieving loop cycles by filtering and reusing drained water to minimise the environmental impacts of green wall maintenance.

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Appendix

Appendix A

Figure A- 1 Number of daily total footfall counts in two monitored classrooms and days when the rooms were mechanically heated

	Dec		Jan		Feb		Mar		Apr		May		Jun		July		Aug		Sep		Oct		Nov	
Date	Green	Ref	Green	Ref	Green	Ref	Green	Ref	Green	Ref	Green	Ref	Green	Ref	Green	Ref	Green	Ref	Green	Ref	Green	Ref	Green	Ref
1	0	0	2	0	179	154	190	161	0	0	6	2	0	0	245	220	178	111	0	0	59	100	142	128
2	0	0	4	0	2	0	0	0	349	151	17	5	0	0	99	74	128	76	10	67	166	142	3	0
3	84	78	4	1	0	0	0	0	298	183	24	4	324	240	182	89	2	2	42	110	185	0	0	0
4	6	9	5	3	298	269	347	289	181	162	0	0	123	147	149	139	0	0	21	67	177		156	236
5	62	31	0	0	335	144	281	117	152	222	0	0	178	98	232	132	28	60	15	126	0		55	132
6	72	9	0	0	365	120	310	213	0	0	0	0	160	122	0	0	116	291	11	48	0		202	183
7	62	4	3	2	208	165	173	158	0	0	7	3	196	117	0	0	2	50	0	0	137		181	141
8	0	0	6	5	192	171	180	151	235	277	20	9	0	0	251	237	15	5	0	0	111		135	123
9	0	0	1	3	0	0	0	0	106	97	2	1	0	0	122	152	14	8	29	7	231		0	0
10	13	3	8	9	0	0	0	0	348	194	2	1	276	255	198	106	0	0	209	19	167		0	0
11	73	75	7	21	310	331	344	262	131	140	0	0	123	132	183	159	0	0	76	7	184		142	211
12	21	5	0	0	326	156	233	141	110	166	0	0	182	137	240	118	10	16	10	24	0		74	134
13	1	2	1	0	339	275	359	219	3	98	4	8	180	144	0	0	7	7	132	3	0		237	191
14	2	0	10	5	203	190	235	150	0	0	17	10	176	103	0	0	13	3	17	0	9		150	163
15	2	0	6	5	171	154	249	169	2	52	32	5	0	0	304	268	243	3	28	0	98		148	124
16	0	0	9	2	2	0	0	0	2	4	20	19	0	0	121	143	70	15	34	50	239		0	0
17	2	7	6	3	0	0	0	0	83	60	4	3	262	198	104	82	2	0	54	8	155		0	0
18	2	2	70	1	291	291	345	270	2	40	0	0	103	147	186	134	0	0	24	2	157		178	216
19	2	2	0	0	265	116	237	146	18	8	0	0	184	99	250	138	2	0	67	6	0		9	8
20	4	2	0	0	317	202	325	197	0	0	305	214	286	153	0	0	32	11	72	17	0		270	207
21	8	5	2	4	227	172	196	173	0	0	118	85	121	130	0	0	5	16	0	0	159		152	185
22	0	0	3	3	92	182	204	164	10	6	255	140	0	0	223	178	17	32	0	0	55		165	162
23	0	0	21	3	0	0	0	0	4	6	148	152	0	0	122	117	10	25	145	347	251		0	0
24	0	0	101	7	0	0	0	0	10	6	189	126	279	212	140	75	0	0	82	158	165		0	0
25	0	0	11	4	349	236	376	325	4	1	0	0	112	82	159	167	0	0	222	184	147		136	204
26	0	0	0	0	252	102	248	123	12	4	0	0	196	174	183	155	0	0	142	165	0			
27	0	0	0	0	319	223	348	230	0	0	0	0	168	114	0	0	16	82	183	169	0			
28	0	0	295	350	173	162	199	153	0	0	118	104	177	145	0	0	28	57	0	0	178			
29	0	0	223	217			0	0	2	2	195	123	0	0	268	160	6	5	0	0	59	4		
30	0	0	280	154			0	0	5	4	161	175	0	0	81	64	5	3	136	267	226	201		
31	0	0	222	190			0	0			174	89			174	47	0	0			167	93		

Days when the heating was on

Days when the heating was off & occupants > 10

Weekends & Holidays when the heating was left on

Appendix B

The diagram below shows the monitored section of the building's wall and the locations where measurements were taken on the external surface of the wall.

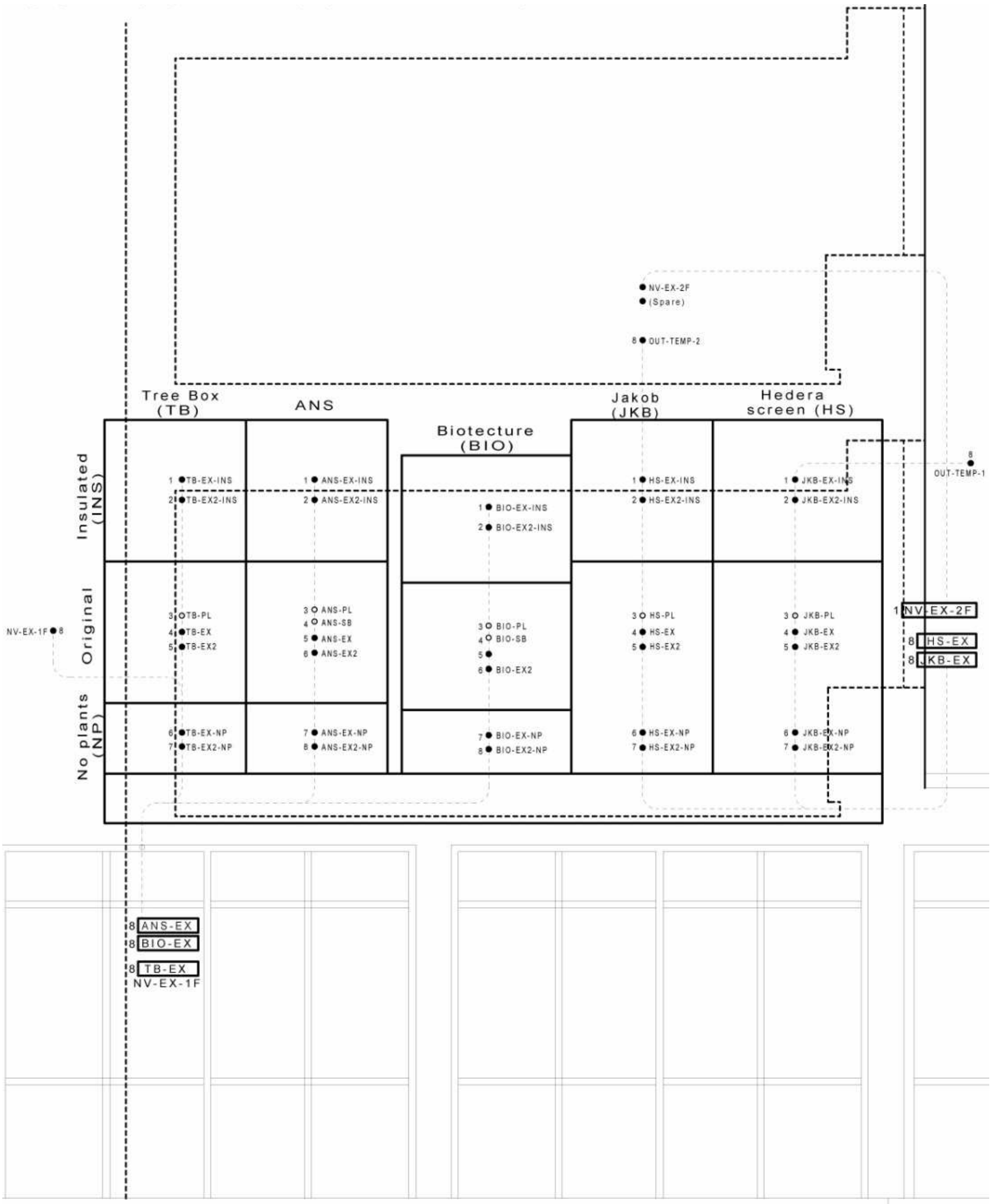


Figure B- 1 Elevation plan of the monitored section of the wall, showing locations of thermocouples measuring external wall surface temperatures

The following diagram shows the locations where measurements were taken on the internal surface of the wall inside two classrooms. Internal wall surface temperatures were measured in corresponding locations to the external wall surface measurements. Wall surface temperatures of the non-vegetated section of the wall were taken in the centre of the reference wall at three different heights again corresponding with the locations where thermocouples were placed in line for measurements of the three variations of each system on the first floor wall. Those measured points on the non-vegetated section are defined as NV- IN/ IN2/ IN3 -2F on the drawing.

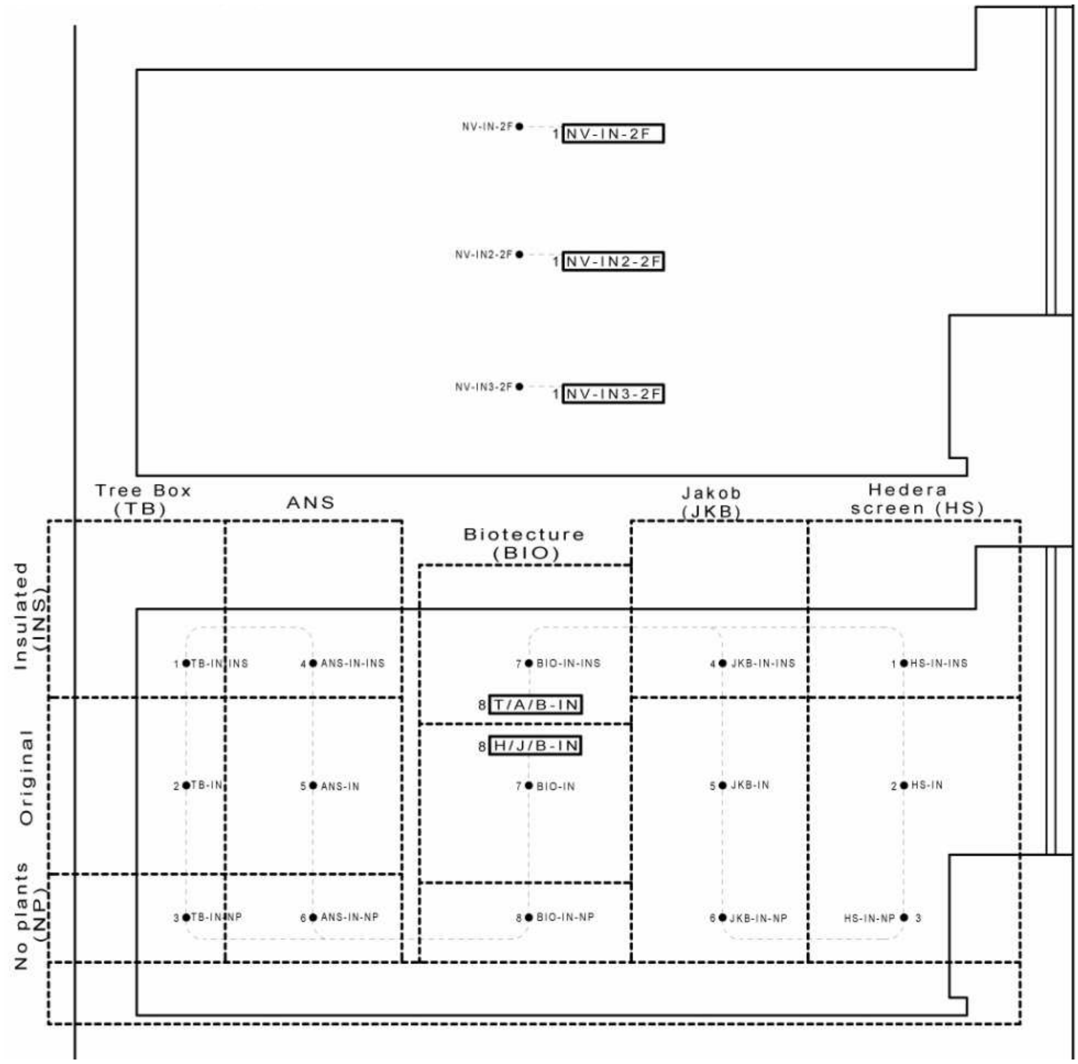


Figure B- 2 Elevation plan of the monitored section of the wall, showing locations of thermocouples measuring internal wall surface temperatures

Appendix C

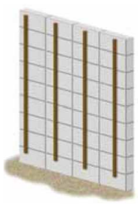
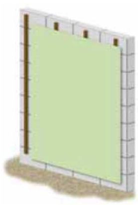
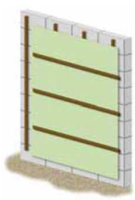
The following tables shows the key components that were used in the irrigation system for the test beds.

Component	Manufacturer	Type
Pump	Grundfos	DAB 6-600
Controller	Heron	Mi8 – Flow Valve Ext
Solenoid Valves	Rain Bird	¾" 075-DV c/w 9v latching solenoid
Pressure Regulator	Rain Bird	¾" Filter 2 bar 75 micron
Solenoid	Manifold	Dura ¾" BSP
Feed Pipe	Revaho	25mm LDPE 13bar
Drippers	Rain Bird	XF 2.3lt/h
	Metzerplas	DP 1.6lt/h
	ANS	CUST 0.8lt/h
Lateral Pipe	Revaho	16mm LDPE 8bar
Lateral Pipe Fittings	Rain Bird	16mm compression
Tavlit		16mm barbed

Appendix D

Three living wall systems of the test beds were mounted on the observed wall following standard methods widely used by regular installers. The table below shows the process of living wall installation which was used in the construction of these test beds.

Figure D- 3 Process of the living wall test beds installation
(Source: ANS Group 2010)

		First, two horizontal beams were bolted onto the structure of the building at the height of the living wall test beds (2.5 meters apart).
1		50mm x 100mm pressure treated softwood battens were fixed onto the beams at the top and the bottom. (Ordinarily, these battens are directlly fixed to the wall structure) The gaps between battens for a meter high from the top of the system were filled with 100mm insulation panels.
2		Waterproof membrane (Compost and Trough) and a weatherproof board (Hydroponic) were fixed on the battens. This would prevent rain and excess irrigation water to permiate into the space behind the system, and protect the building wall surface and insulation panels from getting damp.
3		All three living wall systems required specially designed fixing rails. The rails were placed on the surface and fixed onto the battens behind the waterproof mambrane.

4		Pre-planted living wall panels were mounted from the bottom row to the top. After each row was mounted, drip irrigation tubes were layed horizontally along the top of the panels (Compost and Hydroponic systems) or each row of troughs (Trough system).
5		After completing the installaion of living wall panels, horizontal irrigation tubes were connected to vertical feeding pipes. 150mm high and 150mm deep gutters for drainage were fixed along the bottom.

Ivy screen:

At the bottom of the Ivy screen unit, there was a fibrous trough where the roots of pre-planted climbers had grown inside. The biodegradable trough was placed in the 300mm high and 300mm deep container which was fixed onto the wooden battens. The steel grid panel with Ivy foliage trailing upwards was then fixed onto the battens behind the system using metal brackets.

Figure D- 2 Installers fixing a black sheet of waterproof membrane for Compost and Trough systems, and a grey weatherproof board for the Hydroponic system.

White insulation panels between battens can be seen above the board. The top end of insulation panels were later covered by waterproof membrane for protection.

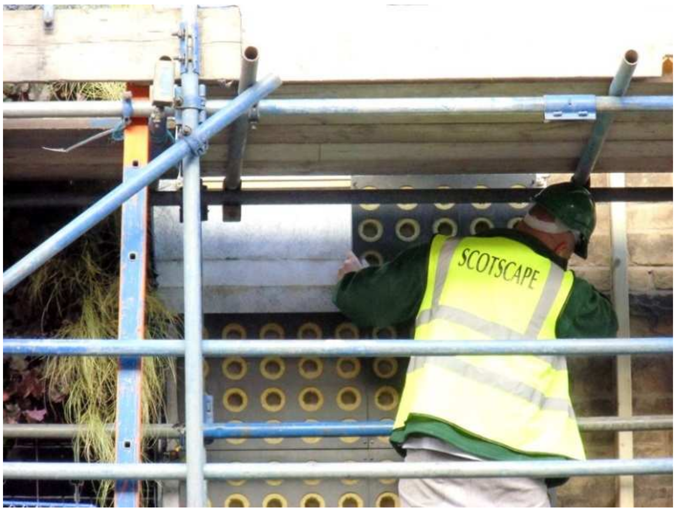


Figure D- 3 Installation of hydroponic panels. The panels are usually pre-planted although plants were inserted into the ‘pockets’ in situ for the test bed due to the limited installation time and lengthy delivery time.

Figure D- 4 Test beds after the installation of living wall panels. Gutters and containers were placed at the bottom of the systems to collect excess water discharged from each system

Figure D- 5 The test beds on completion (2012)

Publications

This thesis contains the work in the following publications:

Yoshimi, J., and Altan, H. 2011. Thermal simulations on the effects of vegetated walls on indoor building environments. *12th Conference of International Building Performance Simulation Association*, Sydney, Australia, 1438-1443.

Yoshimi, J., and Altan, H. 2011. Experimentations of the effects of green roofs on building thermal environments in a cold climate. *1st National Green Roof Student Conference*, Sheffield, UK, 1-7.

Yoshimi, J., and Altan, H. 2012. The Thermal Benefits of Green Roofs in the UK Climate. *World Green Roof Congress 2012,* Copenhagen, Denmark.

Yoshimi, J., and Altan, H. 2014. An Observational Study on the Thermal Benefits of Green Walls in the UK Climate. *1st International Green Wall Conference*, Stoke on Trent, UK.

Altan, H., John, N. and Yoshimi, J. 2015. Comparative Life Cycle Analysis of Green Wall Systems in the UK. *2nd International Sustainable Buildings Symposium,* Ankara, Turkey, 991-999 (ISBN: 978-975-507-278-4).