Final Report

Study of Thermal and Energy Performance of Green Roof Systems

Dr. Sam C. M. Hui

Department of Mechanical Engineering
The University of Hong Kong
Pokfulam Road, Hong Kong

December 2009

For any enquiries about the study, please address to the following person:

Dr. Sam C. M. Hui
Department of Mechanical Engineering
The University of Hong Kong
Pokfulam Road
Hong Kong
Email: cmhui@hku.hk
Tel: (852) 2859 2123 Fax: (852) 2858 5415

CONTENTS

Executive Summary

The purpose of this study is to investigate the thermal and energy performance of green roof systems in Hong Kong. The scope of work includes assessment methods, field studies and measurements on three green roof sites suggested by EMSD and one pilot green roof site proposed by HKU. To develop the research findings, efforts have been made to review the literature and technical information in other countries including Canada, Germany, Greece, Japan, Singapore and USA.

(a) Key Green Roof Concepts

Green roofs are living vegetation installed on the roofs and they are layered roofing systems that include waterproof and root-resistant membranes, a drainage system, filter cloth, growing media and plants. They can block solar radiation, and reduce daily temperature variations and thermal ranges between summer and winter.

Modern roof greening has two main types: intensive and extensive. Extensive green roofs are shallower systems of 60-200 mm depth, with a weight of 60-150 kg/m², with lower capital cost, no added irrigation and lower maintenance. Intensive green roofs range from 150 to 1000 mm in depth, with a weight of 180-500 kg/m² and are able to support a wider range of plants, though demanding more maintenance.

The thermal effects of green roofs can be divided into two aspects:

- Direct effect to the building (internal) - the heat transfer through the roof to the building interior which is the concern on building energy use.
- Indirect effect to the surrounding environment (external) - the heat transfer from the roof to the surrounding environment which is the concern for urban heat islands. When the urban temperature is reduced, it will benefit all the buildings in the area or city and enhance energy conservation.

(b) Literature Study

The heat flux transfer of green roofs is governed by four mechanisms: shading, thermal insulation, evapotranspiration and thermal mass. The thermal and energy performance of green roofs has been studied world wide using three different approaches: field experimentation, numerical studies, and a combination of laboratory or field experiments with numerical models. In general, of the total solar radiation absorbed by the green roof, about 27% is reflected, 60% is absorbed by the plants and the soil through evaporation, and 13% is transmitted into the soil.

The literature review studies indicated that green roofs can substantially reduce the roof surface temperatures and heat flux from a building roof. However, the studies also showed significant differences in the magnitude of the heat flux and energy reduction. For example, from a study of a two-storey building in USA, they found that as compared with a conventional flat membrane roof, the green roof can reduce the heat flux by 18% to 50%. Also, a simulation study of a green roof on a 5-storey office building in Singapore showed annual energy consumption savings of 1% to 15% depending on characteristics of the green roof.

Green roof systems could contribute positively to the mitigation of urban heat island and enhancement of building thermal and environmental performance. It is found from other research that green roofs have a greater potential for reducing heat gain rather than preventing heat loss in the fall and winter.

(c) Field Studies and Measurements

Investigation was carried out on three green roof sites proposed by the EMSD with retrofitting green roof projects in existing government buildings and one pilot green roof project in a school building proposed by the HKU. These green roof sites represented different types of designs and situations for the application of extensive and semi-intensive green roofs. To assess the thermal and energy performance, suitable instrumentation and methodology have been determined for carrying the measurements in July to September 2009.

Table E1 shows a summary of daily temperature fluctuations identified at the green roof sites. The measurements results showed that the green roofs can significantly moderate the daily temperature fluctuations experienced by the roof membrane. Maximum temperature attenuation (i.e. daily temperature fluctuation of bare roof versus that of green roof) of 9.8 °C (at 4/F of APB Centre) to 18.4 °C (at NTK Building taller plants) was recorded. However, during the night time, the cooling effect of the green roof diminished.

Table E1. Daily temperature fluctuations at the green roof sites

Site	Date	Daily temperature fluctuation (°C) (daily maximum temperature – daily minimum temperature)			
		Ambient	**Bare roof**	**Green roof (short plants)**	**Green roof (taller plants)**
Ngau Tau Kok (NTK) Building	3 Aug 2009	5.4 (35.7 – 30.3)	25.4 (54.1 – 28.7)	8.5 (37.2 – 28.7)	7.0 (33.8 – 28.8)
APB Centre 4/F	8 Aug 2009	7.4 (36.1 – 28.7)	13.0 (42.9 – 29.9)	3.2 (31.5 – 28.3)	N/A
Yuen Long Govt Primary School	16 Aug 2009	7.3 (34.8 – 27.5)	17.8 (43.4 – 25.6)	5.6 (36.0 – 30.4)	1.0 (30.1 – 29.1)
St. Bonaventure Catholic Primary School	8 Sep 2009	7.7 (34.0 – 26.3)	31.3 (55.8 – 24.5)	18.1 (44.4 – 26.3)	11.3 (36.1 – 24.8)

Note: For Yuen Long Government Primary School, short plants refer to the pavement grass area; taller plants refer to the planter area. For St. Bonaventure Catholic Primary School, short plants refer to the sedum light weight extensive green roof; taller plants refer to the urban farming box.

Moreover, it was observed that the soil moisture content at the Ngau Tau Kok Building green roof site varied significantly. The drying of green roof plants and soil will affect the thermal effect because low water content in the soil, poor vegetation cover and plant health do not provide adequate evaporation to consume heat. When the soil bases are ultra-thin and very dry, the so-called “inversion phenomenon” may occur, promoting more heat into the building. Thus, the moisture and maintenance of green roof are very important to ensure healthy plants and performance.

In the correct climate, the adiabatic effect of a green roof is significant, and can help reduce the need for air conditioning. However, accurate estimates of energy savings must be made based on the water content of the soil at any given time.

(d) Numerical and Simulation Models

The overall thermal transmittance, U-value, is an important concept for thermal performance in building design. It represents how well an element conducts heat from one side to the other, which makes it the reciprocal of its thermal resistance.

Based on a steady-state Fourier theory in one dimension, the U-values of the green roof sites were estimated (see Table E2). The contribution of the green roofs varies from 16% (10/F of APB Centre) to 42% (Yuen Long Government Primary School), depending on the soil thickness and roof construction.

Table E2. Major results of U-value calculations

Ref.	Description*	U-value ($W/m^2.K$)	% Change**
1	NTK Building -- bare roof	2.433	
	NTK Building -- green roof 100 mm soil & short plants	1.772	- 27.2%
	NTK Building -- green roof 150 mm soil & taller plants	1.646	- 32.4%
2a	APB Centre, 4/F – bare roof	1.228	
	APB Centre, 4/F -- green roof 100 mm soil & sedum plants	1.020	- 16.9%
2b	APB Centre, 10/F -- bare roof	1.194	
	APB Centre, 10/F -- green roof 100 mm soil & sedum plants	0.997	- 16.5%
3	YLGPS -- bare roof	2.166	
	YLGPS -- green roof, pavement area, 92 mm soil & grass	1.701	- 21.5%
	YLGPS -- green roof, planter area 350 mm soil & tall plants	1.248	- 42.4%
4	SBCPS -- bare roof	2.830	
	SBCPS -- green roof (very light weight) 50 mm soil	2.069	- 26.9%

Note: * Building roof is included in the calculation of U-values for different types of green roofs
** % Change = percentage change of U-value as compared to the respective bare roof

For the heat transfer of roof elements, if the roof is very well insulated or if there is a ventilated space between the roof surface and the building interior, then adding a green roof will provide no further significant increase in thermal resistance. The choice of materials in the planted part of the roof does not greatly influence the thermal behaviour of a thermally insulated roof. But when the roof is not thermally insulated, the influence will be more significant. To illustrate this, Table E3 compares the U-values of very light weight green roof, urban farming box and fabric glass insulation panel.

Table E3. U-value calculations for SBCPS with urban farming and insulation panel

Ref.	Description*	U-value ($W/m^2.K$)	% Change**
4	SBCPS -- bare roof	2.830	
	SBCPS -- green roof (very light weight)	2.069	- 26.9%
i)	SBCPS -- green roof (urban farming box on bare roof)	1.439	- 49.2%
ii)	SBCPS -- bare roof + fabric glass insulation panel	0.739	- 73.9%
iii)	SBCPS -- green roof (urban farming box on insulation panel)	0.590	- 79.2%

Note: * Building roof is included in the calculation of U-values for different types of green roofs
** % Change = percentage change as compared to the respective bare roof

The roof-envelope ratio impact on green roof energy performance has also been considered. To study how the roof-envelope ratio affects the relative importance of roof thermal load, a building energy simulation model was set up and computations were performed using the Energy-10 simulation software.

It is found that for the topmost floor of the building, the roof thermal load constitutes 15.3% and 24.3% of building electrical energy consumption and building electrical peak demand, respectively. For high-rise buildings, these percentage figures will decrease accordingly. For 10-storey, 20-storey and 30-storey buildings, the percentage of roof load to whole building total electrical energy are only 1.8%, 0.9% and 0.6%, respectively (see Figure E1). Therefore, even if a green roof can reduce the roof thermal load significantly, the overall impact on the whole building energy consumption (the direct effect) is not large for high-rise buildings. However, the indirect effect to urban temperature would be essential when a large scale greening is adopted.

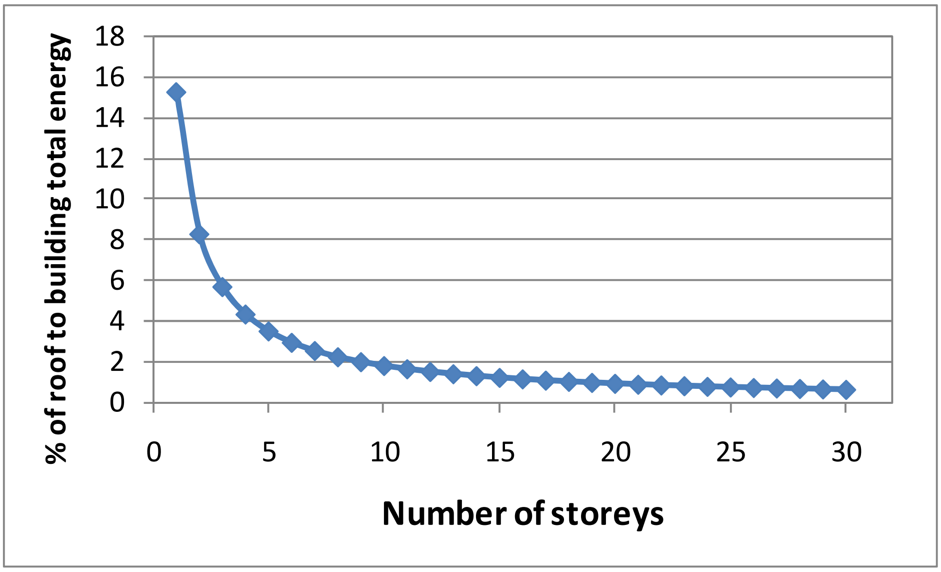


Figure E1. Effects of number of storeys on percentage of roof to building total energy

(e) Assessment of Thermal and Energy Performance

Based on the assessment of U-value and the linear regression equation developed from the building energy simulation, a rough estimation of the effects of green roofs for the four green roof sites is done. The results indicate that when the percentage of green roof area is taken into account, the reduction of the U-value of the whole roof slab is from 1.4% (10/F of APB Centre) to 31.9% (Yuen Long Government Primary School). The corresponding percentage saving of annual total building electrical energy (for top floor only) would range from 0.1% (10/F of APB Centre) to 4.6% (Yuen Long Government Primary School). When more floors are considered, these figures will be reduced further.

The thermal and energy performance of adding a green roof to a bare roof can be studied generally by assessing the thermal resistance of green roofs and the effects on different types of roof structures. The percentage change of the roof U-value (indicates the thermal performance) and the percentage change of annual total building electrical energy use (indicates the energy performance) were calculated and the key analysis results are shown in Figures E2 and E3. Using these two graphs, the effects of adding green roof can be estimated, by checking the U-value of bare roof and the R-value of green roof.

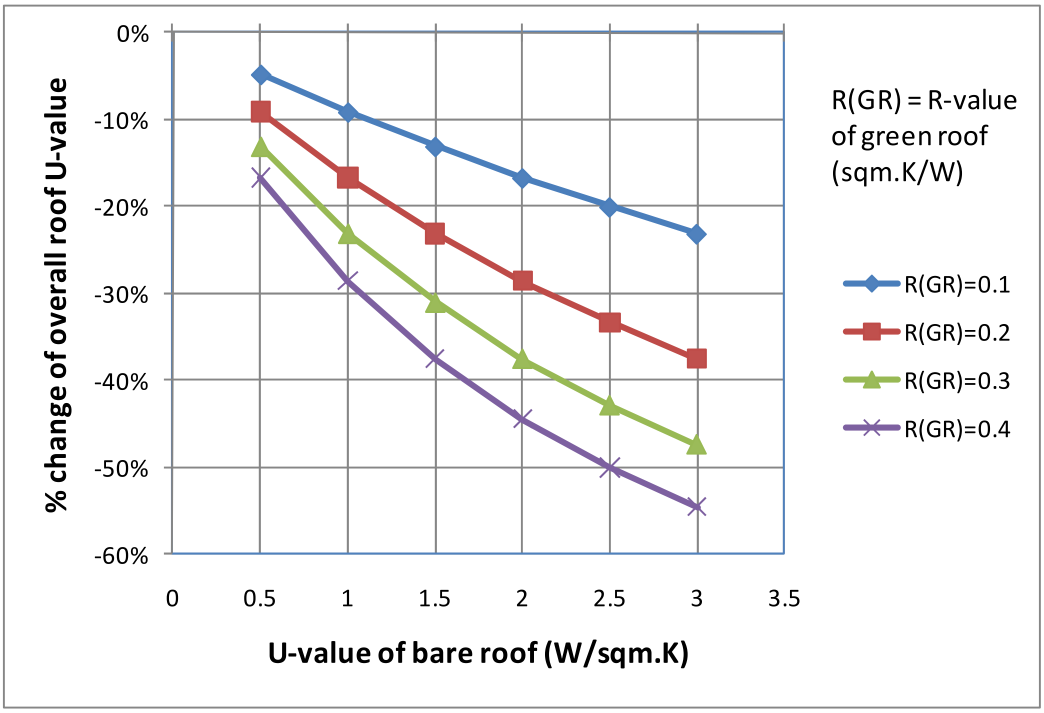


Figure E2. Effect of adding green roof on overall roof U-value

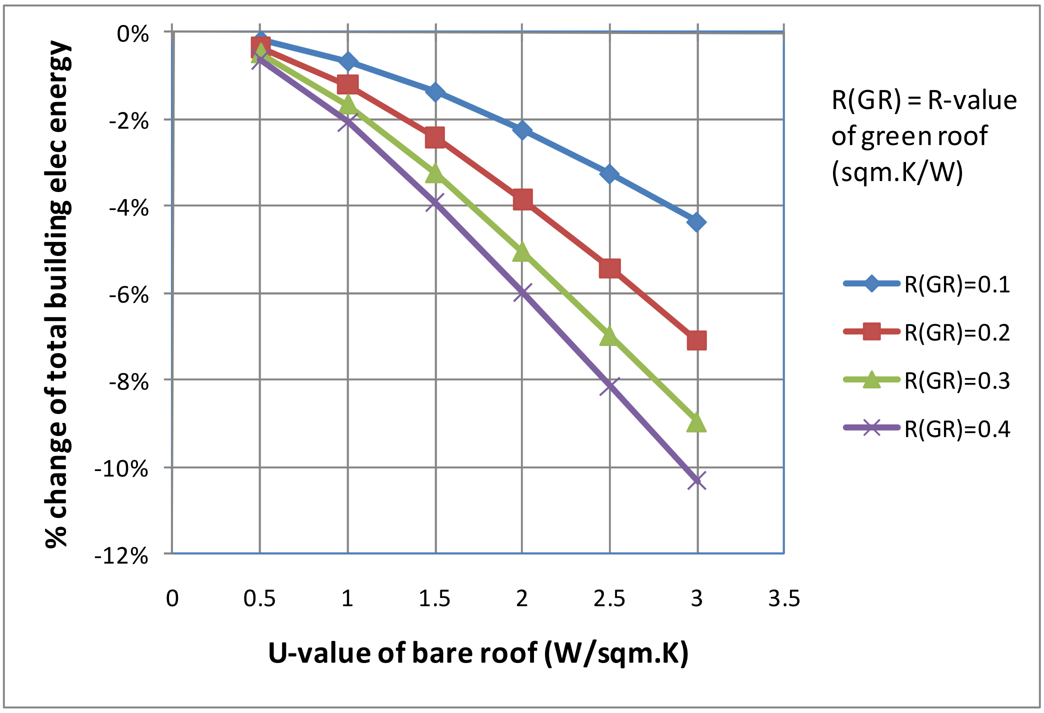


Figure E3. Effect of adding green roof on total building electrical energy use

The U-value calculations have ignored the thermal resistance of the canopy plant layer and the indirect effect of heat transfer from the green roof to the surrounding environment. More detailed simulation models will be needed if these factors are to be considered carefully.

(f) Conclusion and Recommendations

Apart from enhancing the city landscape and environment, mitigating the urban heat island effect and improving air quality, green roof can improve the microlimate and increase the life span of waterproof and insulation facilities on the roof. Consequently, roof greening with a sufficient large scale is conducive to energy conservation and life cycle cost saving for the urban city.

It is found from other research that the placement of photovoltaic panels on green roofs has a double benefit in that the panels shade the roof from excessive sun exposure and high evaporation, thus reducing drought stress of plants and allowing for a wider range of planting choices from full sun to half shade. At the same time, the cooling effect from evapotranspiration of green roof planting enables a 6% higher efficiency of photovoltaic panels and enhances their overall performance.

Green roofs can help reduce three of the four top problems facing the society in the next 50 years: energy, water, and environment. In this way, the green roof technology has a potential to improve quality of population health and welfare in the urban areas with dramatically reduced vegetation. Hopefully this will lead to a holistic green building – better ventilation, shade, micro-climate, less energy reliance for the city.

It is recommended that further studies be carried out to investigate both direct and indirect effects of green roofs, in particular urban heat island effect, in Hong Kong and to review administrative/legislative measures to promote roof and multi-level greening in the urban area.

Acknowledgements

The author would like to thank the following persons for providing supports and assistance to the study and measurements.

Mr. Eddie W. K. Wu, EMSD-EEO
Mr. W. Y. Ho, EMSD-EEO
Mr. T. H. Lam, EMSD-GESD
Ms. Cheung Yuet Ming, Assistant Librarian, LCSD
Mr. William C. H. Choi, EMSD-GESD
Mr. Wallace S. F. Leung, EMSD-GESD
Mr. Raymond Wong, Newland
Mr. Leung Wing Kam, HKU BSE Lab
Miss Chu Ho Ting Carrie, HKU student
Miss Chu Suet Fan Fanny, HKU student
Miss Jia Wei Amy, HKU student
Mr. Tsang Wai Man Wyman, HKU student
Mr. Wong Chuen Wa, HKU student
Miss Yang Xinyan, HKU student
Mr. Yeung Yin Chak Hermann, HKU student

Sincere thanks are expressed to the following organizations for supporting the research study.

Ngau Tau Kok Public Library
APB Centre (To Kwa Wan)
Yuen Long Government Primary School
St. Bonaventure Catholic Primary School (Wong Tai Sin)

List of Figures

Page

List of Tables

List of Abbreviations

ArchSD	Architectural Services Department
CityU	City University of Hong Kong
EEO	Energy Efficiency Office
EMSD	Electrical and Mechanical Services Department
GESD	General Engineering Services Division
HD	Housing Department
HKHS	Hong Kong Housing Society
HKU	The University of Hong Kong
IGRA	International Green Roofs Association
LAI	Leaf area index
LCSD	Leisure and Cultural Services Department
NREL	National Renewable Energy Laboratory
NTK	Ngau Tau Kok
PolyU	The Hong Kong Polytechnic University
SBCPS	St. Bonaventure Catholic Primary School
TKW	To Kwa Wan
UHI	Urban heat island
UV	Ultra-violet
YLGPS	Yuen Long Government Primary School

Nomenclature

a_c	albedo of the surface structural material
c_1	isobaric specific heat of component 1 (moisture) of the mixture (J/kg K)
c_2	isobaric specific heat of component 2 (air) of the mixture (J/kg K)
c_c	building material specific heat capacity (J/kg K)
c_G	specific heat of the soil-water-air mixture (J/kg K)
c_{pa}	isobaric specific heat capacity of air (J/kg K)
D	binary diffusion coefficient (m^2/s)
D_g	diffusion coefficient of water through soil (m^2/s)
$e_s(T_1)$	saturation water vapour pressure at leaf temperature (Pa)
h_a	specific enthalpy of phase a (water) (J/kg)
h_b	specific enthalpy of phase b (steam) (J/kg)
I_1	source of component 1 (moisture) of mass (kg/m^3 s)
K_g	coefficient of permeability of liquid water through soil (hydraulic conductivity) (m/s)
r_a	aerodynamic resistance (s/m)
r_{aH}	convective heat resistance (s/m)
r_s	total stomatal resistance of the canopy (s/m)
q_a	relative concentration of component 1, expressed as specific humidity (kg/kg)
q_c	building material moisture content (kg of the substance/kg of the dry body)
T	temperature (K)
T_a	air temperature (K)
T_l	leave surface temperature (K)
t	time (s)

Greek letters

α_a	coefficient of thermal diffusivity of air (m^2/s)
α_m	diffusion coefficient of moisture in the building material (m^2/s)
ε	ratio of vapour diffusion coefficient to total moisture diffusion coefficient or evaporation number of building material
λ	latent heat of evaporation of water (J/kg)
ρ_a	density of air (kg/m^3)
ψ_p	moisture potential of soil tension (cm)
ω_g	volumetric water content of the soil (soil moisture) (m^3 of liquid water/m^3 of the soil-water-air mixture)

1. Introduction

This study is part of a research project undertaken by researchers at The University of Hong Kong through funding provided by the Electrical and Mechanical Services Department (EMSD). This document reports on the major findings of the project, focusing on the thermal and energy performance of green roofs.

1.1 Background

Many cities are now facing problems of urban heat island (UHI) and lack of greenery space. Hong Kong has extremely high population densities in some urban areas and is thus threatened by an intense UHI effect (Nichol, *et al.*, 2009). Figure 1.1 shows an example of UHI distribution over Kowloon Penninsula in Hong Kong city.

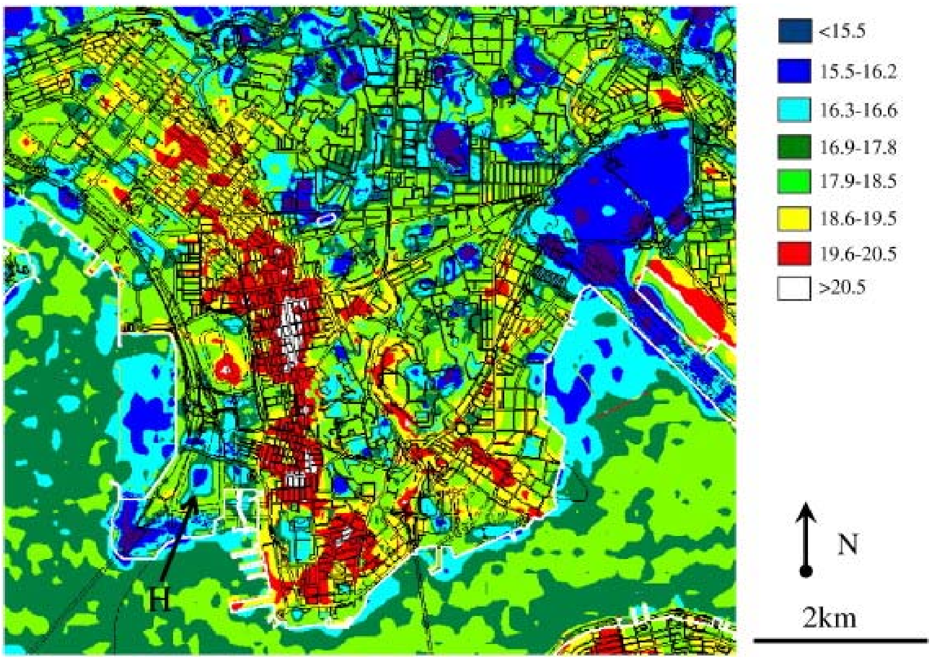


Figure 1.1 Distribution of the scales of surface urban heat island over Kowloon Peninsula in Hong Kong city [Source: Nichol, et al. (2009)]

Green roofs can help mitigate the adverse effects of UHI and bring the nature back to the urban area (Hui and Chan, 2008; Kumar and Kaushik, 2005; Liu, 2003; NRCA, 2007). They not only can help lower urban temperatures, but also can improve aesthetics and urban psychology, as well as reduce pollutant concentrations and noise (Wong and Chen, 2009; Wong, Tan and Chen, 2007).

In Hong Kong, with the growing concerns about environmental issues and the need to promote sustainable urban environment (BD, 2009), green roofs have attracted much attention in our society in recent years (Urbis Limited, 2007). However, the market for green roofs is still developing and immature. There is a lack of good information and understanding on their technical design, effectiveness and actual benefits in our city.

From the experience of the green roof research carried out in the past few years, it is found that the city of Hong Kong has good potential to promote green roofs (Hui and Chan, 2008). However, the current knowledge and understanding of the green roof performance are still not sufficient for the Government and other decision makers to consider the true value of green roof systems and their impacts to the urban environment. It is important that practical research information and data on the thermal and energy performance of green roof systems in Hong Kong can be established from local studies and measurements. Thus this study will address the information gap and provide some hints to evaluate the green roof systems. The research findings will also be useful to other urban cities in the world.

1.2 Objectives

The objectives of this study are:

- To develop methodology and determine suitable instrumentation for assessing the thermal and energy performance of green roof systems in Hong Kong
- To carry out field studies and measurements on three selected green roof sites (i.e. APB Centre, Ngau Tau Kok Municipal Office Building and Yuen Long Government Primary School) and one pilot green roof project (St. Bonaventure Catholic Primary School)
- To evaluate the field studies and analyse measurement results, and prepare a technical report for the whole study

1.3 Report Organisation

This report is divided into six chapters along with the Appendices. Chapter 1 is the introduction which describes the background and objectives of the study. Chapter 2 explains the findings of the literature review. Chapter 3 describes the research methods. Chapter 4 provides details of the analysis results. Chapter 5 discusses the major research findings. Chapter 6 gives conclusions to the study.

The Appendices contain details of the research findings including the key information of green roof systems, a summary of literature review's key findings, methodology and instrumentation plans, information of the green roof sites and the results of relevant measurements, field studies and calculations.

2. Literature Review

A green or living roof is essentially the growing of plants on roof tops. It could range from a spontaneously occurring moss and lichen covered roof to a full-scale roof garden that includes trees, shrubs and hard landscaping features. The insulating properties of soil and plants have been utilised by humans for thousands of years, cooling buildings in Africa and Asia and helping to retain heat in traditional buildings of North Europe and Scandinavia (Forbes, 2006). Traditional urban roof gardens have largely been restricted to growing plants in containers and planters or spreading top soil across the roof. In recent times the development of multi-layered systems which re-create growing conditions across the roof has opened up a variety of planting options (ASTM, 2006).

In recent years, green roof application and development are becoming popular in many countries, as a useful feature for sustainable building technology (Dunnett and Kingsbury, 2008). Figure 2.1 shows some examples of green roof systems in Hong Kong and other Asian countries.


A primary school in San Po Kwong


EMSD Headquarters, Kowloon Bay


Carpark roof of housing estate in Singapore


Putrajava Int. Conven. Centre, Malaysia

Figure 2.1 Examples of green roof systems (photos by Dr. Sam C. M. Hui)

2.1 Overseas Experience

In general, green roofs are layered roofing systems that include waterproof and root-resistant membranes, a drainage system, filter cloth, growing media and plants (NRCA, 2007). They can be created in place or installed using modular sections.

2.1.1 Types of Green Roofs

Modern roof greening has two main approaches: intensive and extensive (Dunnett and Kingsbury, 2008; Weiler and Scholz-Barth, 2006; Zinco, 2000). Extensive green roof systems are typically characterised by shallower system profiles of 60-200 mm depth, with a weight of 60-150 kg/m², with lower capital cost, no added irrigation and lower maintenance. Intensive green roof systems are those characterised by system profiles ranging from 150 to 1000 mm in depth, with a weight of 180-500 kg/m² and able to support a wider range of plants, though demanding more maintenance.

Some of these systems are installed as pre-cultivated vegetation blankets rolled out on site or constructed and planted by hand when insitu on roofs (Loh, 2009). Interlocking modular systems are also developed in recent years to suit particular site conditions (Hui and Chan, 2008; Velazquez, 2003). Appendix I describes the different types of green roof systems in details.

2.1.2 Structure of Green Roofs

The thermal properties of green roof depend on the design and local conditions. Figure 2.2 shows the typical structure of extensive green roof (Hui, 2006). The thermal insulation layer is optional and will be needed according to the climatic conditions and local thermal efficiency regulations. Table 2.1 describes the functions of the major components of the green roof.

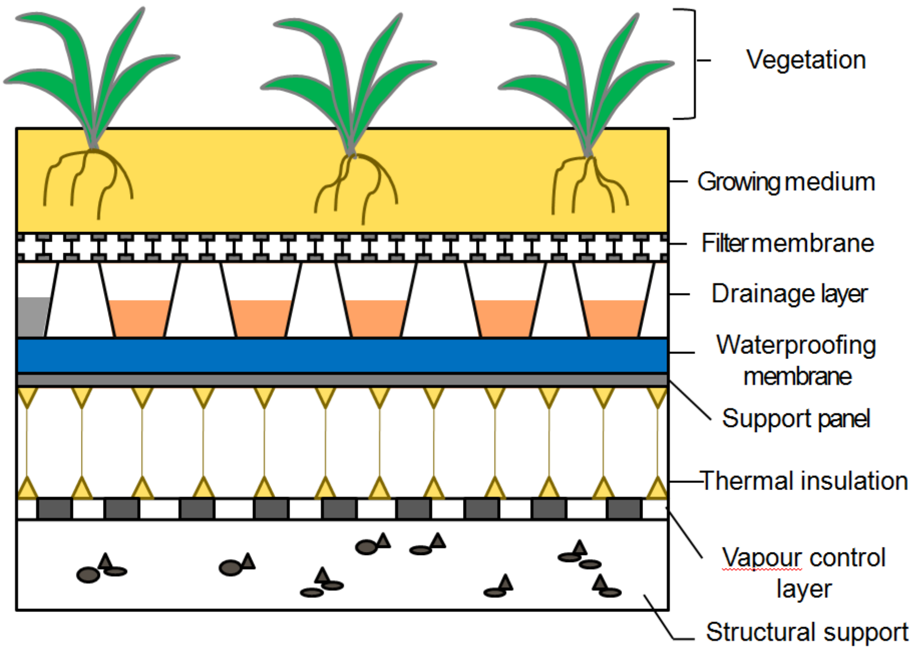


Figure 2.2 Typical structure of extensive green roof

Table 2.1 Major green roof components

Layer	**Functions**
Vegetation	Various types of vegetation could be chosen for intensive or extensive systems. Shrubs, coppices and tress can be found in intensive systems; while grasses that require low maintenance and capable of self-propagation are usually used in extensive systems.
Substrate/ Growing medium	Soil is usually used for the accommodation of roots of plants to absorb water and support plant growth.
Filter sheet	Avoid fine soil or other substances get into the drainage layer to ensure the efficiency of drainage layer.
Drainage layer	Act as a water reservoir to retain water to certain level and can drain out excess water.
Moisture mat	Provide an additional measure to retain water besides the drainage layer.
Root resistant membrane	The membrane can be a chemical agent of a physical root barrier. It is essential in the green roof system to prevent the root of plant from penetrating into the roof structure, which will lead to water leakage problem and even damage to the building structure.

2.1.3 Benefits of Green Roofs

Green roof systems are living vegetation installed on the roofs and could contribute positively to the mitigation of urban heat island and enhancement of building thermal and environmental performance (Hui, 2006). The vegetation and the growing medium in the green roof keep the roofing membrane cool in the summer by shading, insulating and evaporative cooling (Liu, 2002). Therefore, the green roof can significantly moderate the daily temperature fluctuations experienced by the roof membrane.

Green roofs could provide many benefits to the society (Banting, *et al.*, 2005; Doshi, *et al.*, 2005). They have a potential to:

- reduce energy demand on space conditioning
- reduce storm water runoff
- expand the lifetime of roofing membranes
- reduce the urban heat island effect in cities
- improve air quality
- add aesthetic appeal

Green roofs have been proven to protect the roofing membrane against ultra-violet (UV) radiation, extreme temperature fluctuations and puncture or physical damage from recreation or maintenance. The vegetation can also alleviate air and water quality problems by filtering pollutants through the leaves or the roots. In addition, vegetation in urban areas has been shown to increase mental well being, biodiversity and residential property values (Bass and Baskaran, 2003).

2.1.4 Research on Thermal and Energy Performance

The study of green roofs involves several disciplines such as building science, heat transfer, atmospheric science, horticulture and air quality. Because of the complex processes within green roofs, in order to obtain their multiple benefits to the society, research studies have been carried out in many countries in the past decades, trying to understand the properties and performance of different green roof systems. Please refer to the 'References' section for further information of the useful literature. Appendix II gives a summary of key findings from the literature review. The key references or research papers have been identified and studied. They are divided into geographical areas including Europe, North America and Asia (see Tables A2.1, A2.2 and A2.3).

In addition, green roofs have been investigated for their effects on building energy costs (Alcazar and Bass, 2005; Lazzarin, Castellotti and Busato, 2005; Martens, Bass and Alcazar, 2008; Niachou, *et al.*, 2001; Santamouris, *et al.*, 2007; Spala, *et al.*, 2008). The thermal performance of green roofs has been studied world wide using three different approaches: field experimentation, numerical studies, and a combination of laboratory or field experiments with numerical models. Table 2.2 describes the main characteristics of these approaches. Among these three approaches, field research has the advantage of accurately measuring the thermal performance of a specific green roof in specific weather conditions. However, the latter argument unfortunately restricts the applicability to use the results from the field studies to different green roof systems or weather conditions.

Table 2.2 Three approaches to study thermal and energy performance of green roofs

Approach	**Main characteristics**	**Examples**
Field experimentation	Measurements on green roof sites or suitable locations, with specific time period and weather conditions.	Köhler (2006); Köhler, *et al.*, (2002)
Numerical studies	Heat and mass transfer models are often used to represent the green roof system. Other computer simulation techniques, e.g. building energy simulation and computational fluid dynamics (CFD), may be employed.	Del Barrio (1998); Sailor (2008); Wong, *et al.* (2003b)
Laboratory or field experiments	Controlled experiments and/or laboratory testing are carried out. Analysis with numerical models.	Connelly and Liu (2005); Fang (2008); Lazzarin, Castellotti and Busato (2005); Liu (2003)

All the reviewed studies concluded that green roofs can substantially reduce the heat flux from a building roof. However, the studies also showed significant differences in the magnitude of the heat flux reduction. Furthermore, there are other major differences between each study; for example, the factors that have a significant role in reducing the cooling loads in green roofs.

By mimicking the microclimate around and inside buildings using computer modeling, Alexandri and Jones (2008) found that green roofs and walls can cool local temperatures by 3.6°C to 11.3°C, depending on the city location. They also compared local temperatures when buildings were made of bare concrete with when the concrete was covered in vegetation. It is believed that humid climates like Hong Kong can benefit from green surfaces, especially when both walls and roofs are covered with vegetation.

2.2 Basic Principles

In order to understand the thermal effect of green roofs, it is necessary to study the basic principles of building heat transfer and the theory of green roof model. A brief summary of the key principles and information is described below.

2.2.1 Building Heat Transfer

From a thermal point of view a building can be looked upon as a modifier of the climate (Davies, 2004). The fabric of the building including external walls and roofs serves as a filter or buffer and provides the passive function which affects the internal environment and determines the cooling or heating load. The thermal behaviour of buildings at steady-state can be described by using the thermal circuit theory and the Fourier continuity equation in one dimension.

By Fourier's first law, heat flux density for a steady state flow is directly proportional to the temperature gradient:

$$\partial q = -\lambda A \frac{\partial T}{\partial Z} \qquad (2.1)$$

where q = heat flux (W)
λ = thermal conductivity ($Wm^{-1}K^{-1}$)
A = area (m^2)
T = temperature (K)
Z = distance or thickness (m)

After integrating, it becomes:

$$q = \left(\frac{\lambda A}{z}\right)(T_1 - T_2) \qquad (2.2)$$

If the overall heat transfer coefficient or thermal transmittance (*U*) is used, then

$$U = \frac{\lambda}{z} \qquad (2.3)$$

$$q = UA(T_1 - T_2) \qquad (2.4)$$

The term '*U*' represents overall thermal transmittance or conductance from the outside to inside covering all modes of heat transfer. From the above equation, 'U-value' can be defined as the rate of heat flow over unit area of any building component through unit overall temperature difference between both sides of the component. The U-Value is an important concept in building design. It represents how well an element conducts heat from one side to the other, which makes it the reciprocal of its thermal resistance.

Thus, the U-Value can be calculated by:

$$U = \frac{1}{\sum \text{Thermal resistances}} \qquad (2.5)$$

In the steady state calculation it is assumed that the conductivity in some layer is constant and the temperature gradient is then uniform.

2.2.2 Heat Transfer of Roof Elements

The heat transfer of roof elements can be divided into two parts:

(a) Heat transfer from the roof to the surrounding environment, which is of concern for urban heat islands; and
(b) Heat transfer through the roof to the building interior, which is of concern for building energy use.

Obviously the heat transfer from the roof to the surrounding environment and the building interior are interrelated to each other. However, if the roof is very well insulated or if there is a ventilated space between the roof surface and the building interior, this linkage is weakened. In such case the reflectivity of the roof surface would have little effect on the building energy use but would still be important relative to mitigating UHI impacts. Figure 2.3 shows the heat balance on a roof surface.

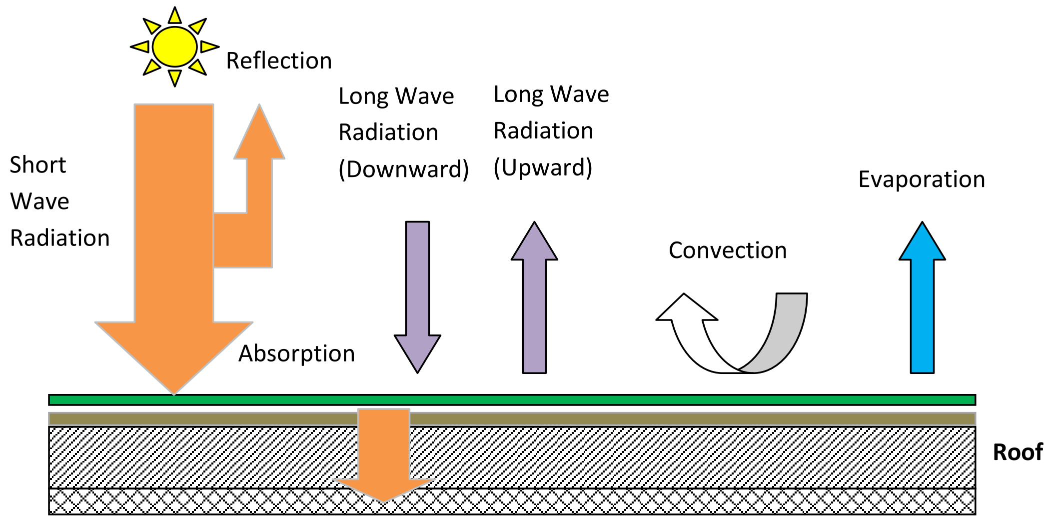


Figure 2.3 Heat balance on a roof surface (adapted from Professor Yasushi Kondo of Musashi Institute of Technology, Japan)

As energy from the sun strikes a roof surface it is either absorbed or reflected back to the sky. The radiative energy reflected to the sky is either absorbed high in the atmosphere or transmitted directly outer space. In any case it is generally agreed that the reflected (from horizontal roofs) portion does not contribute to air conditioning loads or UHI effects.

The solar energy that is absorbed by the roof surface is converted to heat. The heat causes the temperature of the surface to increase until the rate of heat flow from the surface into the building and to the surrounding environment equals the rate of heat gain from absorbed solar radiation. The heat flow into the building is generally by conduction through the material layers of the roof construction and increases cooling loads and decreases heating loads depending on the season.

Heat flows from the roof surface to the surrounding environment by the emission of long-wave radiation to the sky (space and the upper atmosphere) and by convection to the nearby air. It is only the heat convected to the nearby air that is significant to the UHI problem. To reduce the UHI impacts, it is desirable to have a surface with a high emissivity to maximize heat transfer to the sky and thus reduce proportion of the absorbed solar energy that must be transferred by convection to the local air.

Using an implicit, control volume finite-difference method, Al-Sanea (2002) has evaluated and compared the thermal performance of building roof elements subject to steady periodic changes in ambient temperature, solar radiation and nonlinear radiation exchange. A numerical model is developed and applied for six types of typical roof structure in Saudi Arabia. The study results provided useful information to investigate the detailed temperature and heat flux variations with time, the relative importance of the various heat-transfer components as well as the daily averaged roof heat-transfer load.

2.2.3 Heat Transfer of Green Roof

The heat transfer of the green roof is different from that of the bare roof, since the external climatic factor (solar radiation, external temperature, relative humidity and winds) are slowed down and reduced as they pass through the foliage which cover the roof (Eumorfopoulou and Aravantinos, 1998). Large amount of solar energy are absorbed for the growth of plants through their biological functions, such as photosynthesis, respiration, transpiration and evaporation. Figure 2.4 shows the fundamental concepts to explain the thermal properties of green roof.

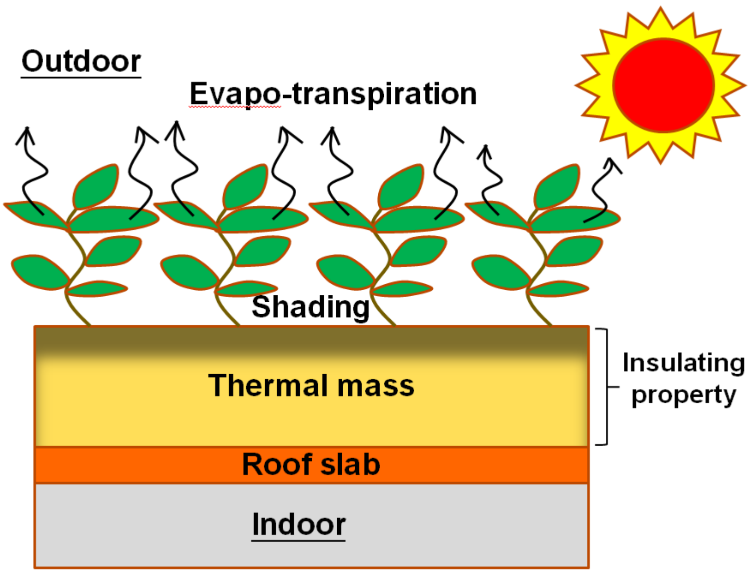


Figure 2.4 Thermal properties of green roof

The major challenge of the green roof study comes from the complex heat flux transfer through the roof by means of four mechanisms (Niachou, *et al.*, 2001).

(a) Shading
(b) Thermal insulation
(c) Evapotranspiration
(d) Thermal mass

Shading is the protection provided by the plants from solar radiation. Thermal insulation is the increment in the thermal resistance of the roof because of the plants and growing medium. Thus heat flux through the roof is reduced. Evapotranspiration is the lost of water by evaporation of water from soil and from plants transpiration during photosynthesis. Thermal mass is a property of a material and refers to its ability to absorb heat; it will affect the cooling/heating load profiles of the building.

The thermal performance of green roofs includes a combined effect of different factors within the plants and the growing medium. As a result, estimation of green roof thermal and energy performance is not an easy task because the thermal properties of a green roof depend on variable factors such as the growing medium and soil moisture content. In order to better understand the situation, there is a need to develop more practical research information and data on the green roof systems in Hong Kong.

2.3 Experience in Hong Kong

In the Chief Executive's Policy Address for 1999 and 2000, the Hong Kong Government undertook to devote more concerted efforts to promote greening, particularly in the urban area, with a view to making Hong Kong a green model city of Asia (see www.gov.hk/en/residents/environment/sustainable/greening.htm). The Government's greening policy aims to enhance the quality of our living environment through active planting, and proper maintenance and preservation of trees and vegetation (BD, 2009). The target is to bring noticeable improvements in urban greenery, improve the quality of existing greened areas and maximize greening opportunity during the planning and development stages of public works projects. Private sector and community involvement will also be encouraged to further promote greening, so that every practical opportunity could be explored for provision of greenery.

In fact, intensive green roofs, in the form of roof gardens, are a well established phenomenon in Hong Kong, often as landscape podiums in residential buildings (Urbis Limited, 2007). Many public open spaces are also built either wholly or partially on structure. It is therefore not surprising that Hong Kong already has as high a percentage of intensive green roof coverage as any other city. However, since there is no direct government requirement or industry incentive in Hong Kong for private developers to build extensive green roofs, they are still limited in Hong Kong and their application has yet to be promoted. A summary of the efforts by the relevant bodies to develop and promote green roof projects is described below.

2.3.1 Roof Greening By ArchSD

Being the main government department in Hong Kong responsible for municipal building projects, the Architectural Services Department (ArchSD) has been asked to implement green roof projects for new government buildings as far as practicable. Starting from 2001, the ArchSD has incorporated rooftop or podium landscape designs in new government building projects wherever practicable. About 70 projects with such green features have been completed. These include schools, office buildings, hospitals, community facilities and government quarters. Table 2.3 shows the number of buildings with the green roof features.

Table 2.3 Types of buildings in Hong Kong with rooftop/podium green features between 2001 and 2008 (Source: www.devb-wb.gov.hk/greening)

Types of buildings	**No. of Projects**
School	20
Office building	16
Hospital	6
Community facilities	21
Government quarters	5
Total	68

For those completed rooftop/podium green projects, the scope of greening works aims to enhance the use and design of the respective rooftops/podiums. In most cases, soil layer is placed on the rooftop surface for growing different kinds of plants (see Table 2.4). Generally speaking, this planting method is more cost effective. Potted plants are used when there is space or other kind of constraints, for example, building services installations.

Table 2.4 Breakdown of rooftop/podium green features between 2001 and 2008 (Source: www.devb-wb.gov.hk/greening)

Rooftop/podium green features	**No. of Projects**
Soil layer planting on rooftop surface	56
Pot planting	3
Soil layer planting on rooftop surface and pot planting	9
Total	68

In early 2007, ArchSD had also completed a consultancy study on "Green Roof Application in Hong Kong", focusing on the technical aspects of rooftop landscaping (Urbis Limited, 2007). The primary objective of the study is to conduct a quick review of the latest concepts and design technology of green roofs and recommend technical guidelines adopted to suit applications in Hong Kong to promote public understanding and awareness.

In March 2009, a seminar on greening including the application of green roofs was conducted for interested organizations including professional institutes, property management companies, owners' corporations etc. To assess the horticultural/maintenance requirements on provision of green roofs and the extent of room temperature reduction, ArchSD has completed 18 retrofitting green roof projects for existing government buildings since 2006 and has further identified around 20 projects for completion in 2009.

2.3.2 Roof Greening By Housing Department

Extensive green roofs have been tried out by the Housing Department (HD) in some newly established public housing estate and in some shopping arcades. Indigenous herbaceous plants that can grow more easily were planted with a view to increasing the ecological value of the landscaped area. HD is now evaluating the outcome to consider whether and how roof greening should be extended to other public housing estates with regard to its management, conservation and mosquito elimination. In 2007/08, HD has completed about 420 m^2 of extensive green roof in two new public housing estates. In 2008/09, they have completed about 3,500 m^2 in six new estates. Table 2.5 shows a summary of the green roof installations.

Table 2.5 Green roof in new public housing estates in Hong Kong

Project	Area (m^2)	Location	Types
Tin Shui Wai Area 103 Phase 2	1250	Roof of commercial centre	Turf
Choi Wan Site 1 Phase 1, 2 & 3	500	Roof of carpark, commercial centre, refuse collection compound	Turf, small shrubs and groundcovers
Fanling Area 36 Phase 1 & 2	370	Roof of refuse collection compound	Sedum plants
Un Chau Estate Phase 2 & 4	350	Roof of refuse collection compound	Small shrubs and groundcovers
Eastern Harbour Crossing Site Phase 3	510	Roof of refuse collection compound	Small shrubs and groundcovers
Upper Ngau Tau Kok Estate Phase 2 & 3	530	Roof of refuse collection compound	Small shrubs and groundcovers

Source: Legislative Council Panel on Housing Green roof in the Fu Shan Estate market, paper CB(1) 894/08-09(05), February 2009, available at www.legco.gov.hk

2.3.3 Green Roof Projects By Other Bodies

To encourage roof greening, the Environment and Conservation Fund under the Environment Bureau (www.enb.gov.hk) is open to applications from non-profit making institutions for funding support to greening projects, including roof greening. The Hong Kong Government is also investigating the feasibility of promoting roof greening in private developments through a consultancy study on sustainable building designs which aims at developing guidelines on the subject, and provision of more green features including green roofs is one of the issues under the study.

The Hong Kong Housing Society (HKHS) has incorporated green roof and vertical greening in the design of some of the rehabilitation projects, such as Kwun Lung Lau Phase I & II and Chun Seen Mei Chun (www.hkhs.com). A green roof for schools programme has also been initiated by the Hongkong Bank Foundation in collaboration with The University of Hong Kong (Source: *www.hsbc.com.hk/1/2/cr/community/projects/green_roof*). This HK$5 million programme will create green outdoor classrooms for teachers and students in 10 selected schools in Hong Kong.

A few green roof projects have also been done by the private sector. One example is a living roof garden located in Mongkok for a regional headquarters building of a bank corporation (Source: *www.cif.org/nom2008/nom-2008-11.pdf*). The green roof covered 88% of the roof area and included both extensive (with turf) and semi-intensive (with planter) systems.

2.3.4 Green Roof Research in Hong Kong

The number of research projects in Hong Kong related to green roof is increasing in the past two years, but the research information and impacts are still very limited. Table 2.6 gives a summary of green roof research studies in Hong Kong carried out by the local universities. Most of them focus on field experiments and measurements with the aim to evaluate the benefits and applications of the green roofs.

Table 2.6 Summary of green roof research in Hong Kong

References	University	Key findings
Hui (2004); Hui (2006); Hui and Chan (2008); Hui and Chu (2009)	HKU	Study on the benefits and potential applications of green roof systems in Hong Kong. Development of modular green roofs and assessment of green roofs for stormwater mitigation. Pilot studies were carried out at a construction site office and some school buildings since 2002.
Jim (2007); The Standard staff reporter (2006)	HKU	An extensive green roof was retrofitted on the Runme Shaw Building at HKU in June 2006. It covers about 200 m^2 of flat roof space, divided into three equal square plots planted respectively with turfgrass, groundcover vine and shrub. A series of environmental monitoring sensors were installed.
Luk, *et al.* (2006)	PolyU	Quantitative analysis of green rooftop technology effects on air quality and energy usage in Hong Kong. Experimental green roof sites were set up in the University and another charity organisation. Estimation of the benefits in stormwater reduction and energy savings (by Prof. WAI Wing Hong, Onyx) (on-going)
Not available	CityU	Energy performance and application of green roof systems for buildings in Hong Kong (by Dr. Apple Chan and Dr. T. T. Chow) (on-going)

To illustrate the main concerns and findings of the local green roof research, an example is described as follows.

One of the first academic research specific to the green roof system in Hong Kong was initiated in 2002-2003 at a pilot study project on green construction site offices located at Tsing Yi Island (Hui, 2004). This research was inspired by an extensive green roof demonstration set up in 2001-2002 at the Integer Hong Kong Pavilion, a 2,000 m^2 exhibition and research facility located at the Tamar site in Central.

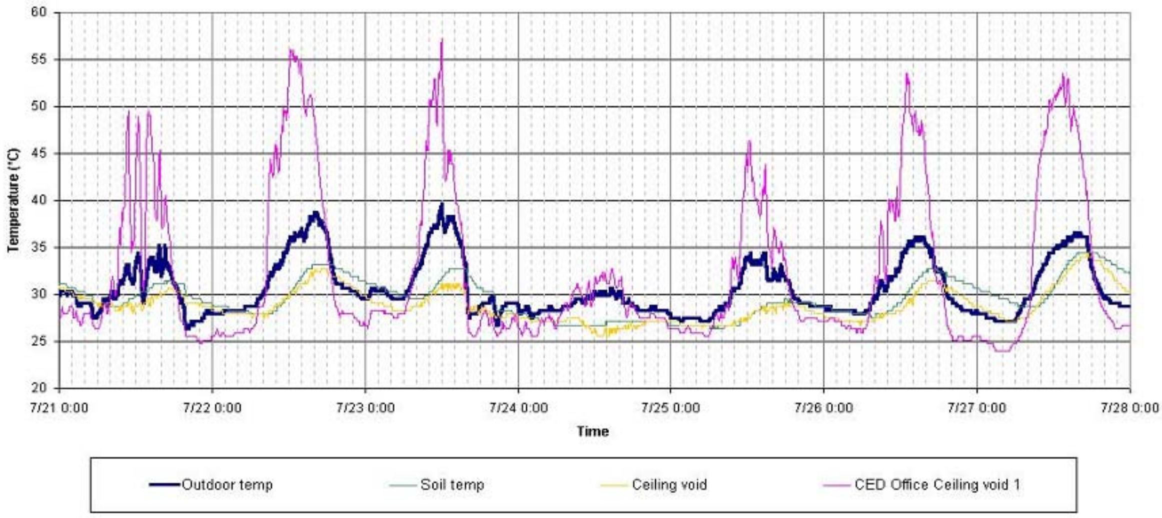
For the research study described in Hui (2004), an extensive green roof system was installed on the sloping roof of a construction site office. The system consisted of metal trays of 200 mm deep and included a substrate formula of light expanded clay aggregate and pumice. Traditional sedum species were planted at first but these did not do well and were quickly invaded by unsightly weeds. Consequently, a slow-growing lawn grass species was then planted which has proven far more effective in preventing invader weeds.

The thermal and energy performance of the green roof has been evaluated by comparing to that of a conventional site office as shown in Figures 2.3 and 2.4. Temperature reduction of up to 25 °C was recorded under the green roof as compared to the conventional roof. This is consistent with the research finding in another study (The Standard staff reporter, 2006).

Green roof on the construction site office

Conventional site office (as the control)

Figure 2.5 Green roof research at construction site offices in Tsing Yi Island



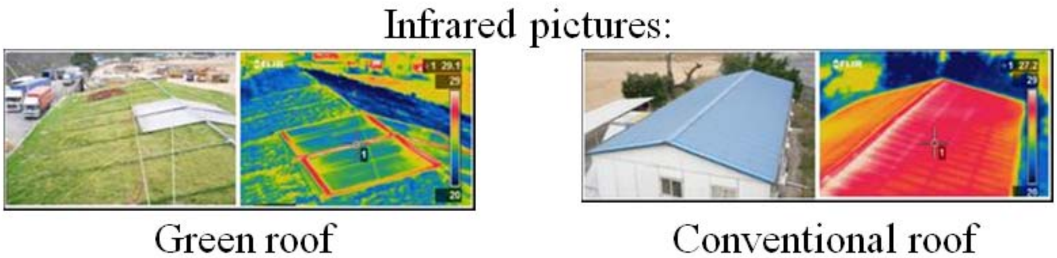


Figure 2.6 Temperature data and infrared pictures of the construction site offices

2.4 Significance of This Study

Since Hong Kong has a sub-tropical climate with hot and humid weather conditions in most of the year, it is believed that the main purpose of the study on thermal and energy performance of green roofs in Hong Kong is to evaluate their cooling effects and potential impacts on air-conditioning energy use inside the building. At the same time, the heat transfer from the green roof to the surrounding environment (known as 'microclimate') should not be neglected since this effect is important for the mitigation of urban heat islands and air pollution problems.

In many countries around the world, the use of green roofs is becoming increasingly common for both new and retrofit buildings. There is widespread recognition and a growing literature of measured data that suggest green roofs can reduce building energy consumption. It is essential to learn from the past and current research experience so as to effectively investigate the issues and develop key strategies to apply the green roof technology.

When the thermal and energy performance of green roofs can be estimated in a scientific and systematic way, it will be easier to design buildings using green roofs. It is also useful to the Government and other policy makers to consider and implement measures and policies to promote urban greenery. It is hoped that the research findings of the current study will be useful to Hong Kong and other urban cities in the world.

3. Research Methods

The research methods used in this project include literature study to extract useful information from overseas and local research references, field studies and measurements to evaluate the practical situation in Hong Kong, as well as numerical and simulation models to develop key concepts and data for the assessment. This strategy is recommended after studying the three approaches adopted in other green roof research in the world (see Sub-section 2.1.2), namely, field experimentation, numerical studies and laboratory or field experiments.

In order to carry out the measurements and assess the green roof performance effectively, care must be taken to develop suitable methodology and instruments for the investigation. Results from the previous studies indicate that the thermal and energy performance is affected by many factors including climatic conditions, site environment and building operation. It is necessary to adopt a combination of research methods so as to evaluate the green roof performance in an effective way.

3.1 Literature Study and Evaluation

As mentioned in Chapter 2 Literature Review, the experience of the green roof research in other countries is very useful to Hong Kong. To extract useful information for this project, efforts have been made to search for and review the literature and technical information on green roof studies and measurements in other countries and cities. The information forms a basis for designing the study methodology and instrumentation (see Appendix III).

From the past experience of the author, it is found that countries which have good experience in green roof research and measurements include Canada, Germany, Greece, Japan, Singapore and USA. In fact, some of them have summer weather conditions similar to that in Hong Kong. Therefore, the literature study has tried to search and identify the references from these countries so that we can develop practical information for Hong Kong (see also the References section). The major findings are summarized and discussed in Chapter 2.

3.2 Field Studies and Measurements

Field studies and experimental thermal measurements were carried out in July to September 2009 in order to assess the practical issues and performance of green roofs in Hong Kong. Three green roof sites were suggested by the EMSD and they are retrofitting green roof projects for existing government buildings (see Sub-section 2.2.1). One pilot green roof project in a school building was proposed by the HKU researchers and this also included a small area of urban farming on the roof (see

Appendix VIII). It can be seen that the four green roof sites have different types of designs and situations for the application of extensive and semi-intensive green roofs. Figure 3.1 shows the pictures of the four green roof sites. Table 3.1 gives a summary of the major characteristics of these sites. Further information about the sites can be found in Appendices IV to VIII.

Ngau Tau Kok Municipal Office Building | APB Centre at To Kwa Wan (10/F) | Yuen Long Government Primary School | St. Bonaventure Catholic Primary School

Figure 3.1 Green roof sites under investigation

Table 3.1 Major characteristics of the green roof sites

Green roof site	Description
Ngau Tau Kok Municipal Office Building	- On top of a public library, at 3/F - Extensive green roof, area: 112 m^2 - Divided into 3 sections and three types of plants - Soil thickness: 150 to 200 mm
APB Centre	- At 10/F (above office) and 4/F (above carpark) - Extensive green roof, area: 206 m^2 (10/F) and 147 m^2 (4/F) - Hardy plants (sedum) are used - Soil thickness: 100 mm
Yuen Long Government Primary School	- On top of classrooms, at 6/F - Roof garden (extensive + semi-intensive), area: 280 m^2 - Grass pavement and planters are used - Soil thickness: 100 mm and 350 mm
St. Bonaventure Catholic Primary School	- On top of an assembly hall - Extensive green roof (modular and built-in, very light weight), 240 m^2 - Hardy plants (sedum) are used; soil thickness: 50 mm - A small area of urban farming (for herb and vegetation) is also set up; the soil thickness is 150 mm and the canopy layer is taller

3.2.1 Duration of Measurements

The experiment was carried out from 30 July 2009 to 12 September 2009. Three sites have 7 continuous days of thermal data logging for each site; one site (Yuen Long Government Primary School) has 4 continuous days of thermal data logging. This period was chosen to represent the hottest season of Hong Kong. The weather during this period was generally good with slight cloud overcast and occasion rain on a few days (see Sub-section 4.2.2 and Appendix X for details).

For two of the green roof sites, APB Centre at To Kwa Wan and St. Bonaventure Catholic Primary School, additional data and information were obtained from the measurements done previously by a sub-contractor of the EMSD and the HKU researchers, respectively. This will provide additional information to assess the performance of green roofs in other seasons and periods of the year.

Arrangement has also been made to collect and study the data and information of the manual thermal measurements done by another EMSD sub-contractor on the three green roof sites suggested by the EMSD. However, these manual thermal measurements were done only for a single day (about 10 hours, at 15 minutes interval) for each site.

The ideal duration of measurements is at least one whole year because the climatic variation can be studied from the annual results. However, in practice, this might not be economical and feasible. Therefore, to resolve the time limitation, short-term measurements can be done and numerical models would be built up to evaluate the key properties and performance over a long-term period.

3.2.2 Other Observations and Information

Before the actual measurements are being conducted, field studies and visits have been done at the green roof sites to collect essential information and assess the local conditions. Observations at the site will provide useful information and data for designing the instrumentation methods, locations and number of measuring points. It is also important to get the cooperation and support of the building owners, managers and users. If they are willing to help, the measurements can be carried out more effectively, with minimum disturbance to the building or business operation.

For the APB Centre roof floor (10/F), EMSD has a subcontractor who has set up the temperature measurement instruments since September 2008. They have provided their data for the period 1 Sep 2008 to 8 Mar 2009 (about 6 months, at 30 minutes interval). These data will be used for analysis of longer term behavior of the specific green roof.

3.3 Numerical and Simulation Models

In order to generalize the findings of this study project to other green roof designs and situations, efforts have been made to develop numerical calculations and simulation models for the analysis of the green roof systems.

3.3.1 U-value Calculations

Based on a steady-state principle for Fourier analysis of the thermal behaviour of buildings (see Section 2.3), an Excel spreadsheet has been developed for the calculation of U-value of the roof construction. This method is used to assess the thermal contribution of the vegetation on the roof in Eumorfopoulou and Aravantinos (1998). Assumptions used in the calculations were taken from the relevant handbooks and references (see Section 4.4 for the results). Figure 3.2 shows the heat flows into and out of a roof; it is the basic concept of the U-value calculation.

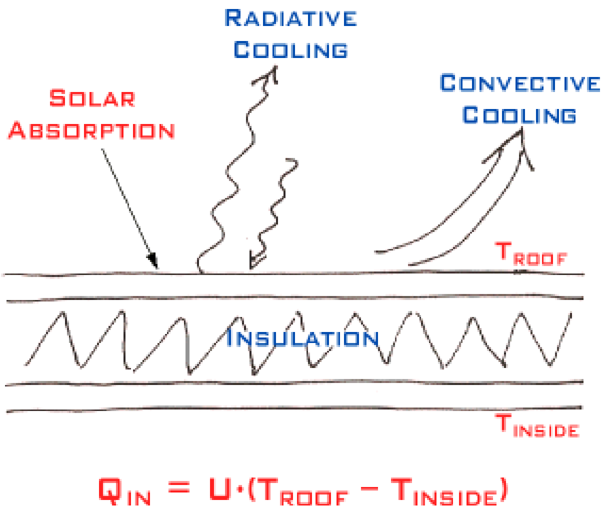


Figure 3.2 Heat flows into and out of a roof (Source: http://eetd.lbl.gov/HeatIsland/)

When studying the thermal performance of green roof, the roof is usually large enough to assume horizontal homogeneity. Therefore, heat and mass fluxes are assumed to be mainly vertical, so that one-dimensional models can be used to describe the thermal behavior of the roof components (Del Barrio, 1998).

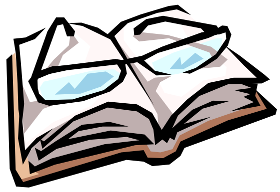
3.3.2 Green Roof Models

To simplify the calculations and analysis, green roof model can be developed by composing the following three elements, together with the coupling models (see also Figure 2.4).

(a) Roof support model
(b) Soil model
(c) Canopy model

The above models represent the real boundary conditions at the interfaces, satisfying the physical constraints of continuity for the state variables and flux densities. Further details can be found in Sections 4.1 and 4.4.

Del Barrio (1998) has proposed a mathematical model of the cooling effect of canopies and the dynamic thermal behaviour of real green roofs. The heat and moisture transfer in soil and the radiant heat exchange in the canopy layer were expressed rigorously in heat and mass transfer equations. The parameters defining the outdoor conditions include solar radiation flux, thermal radiation flux coming from the sky, temperature and moisture content of the air, wind speed and wind direction.



4. Analysis of Results

Current research in the world indicates green roofs have credible benefits of lowering the temperature of a building and its surroundings which in turn lowers a building's energy costs as well as UHI temperatures.

In this Chapter, the analysis results are presented with the aim to compare the theoretical prediction with the actual performance. Firstly, the key findings from other research are identified to form a basis for evaluation in our study. Secondly, the results of field studies and measurements are presented to show the practical issues and situations in Hong Kong. Thirdly, the analysis of green roof performance is generalised using the thermal and energy models.

4.1 Findings from Other Research

The value of absorbed solar radiation transmitted through a bare roof could be as high as 90%. In the summer, a typical gravel-covered rooftop temperature can vary between 60 °C and 80 °C (Peck, *et al.*, 1999). These temperatures increase the cooling load on a building in two ways (Bass and Baskaran, 2003):

(a) Since the internal temperature underneath the roof is typically lower than the temperature above the roof, the heat will always flow through the roof into the building.
(b) Modern buildings are constantly exchanging the internal and external air. Because of the high roof temperatures, the temperature of this external air that is brought into the building's ventilation system may be warmer than the ambient air, requiring additional energy for cooling.

4.1.1 Thermal Protection

The vegetation protects the roof from the thermal loads of solar radiation in summer in three major ways. These are:

(a) their reflective properties;
(b) the convection of the energy absorbed by the plants; and
(c) the evaporation from the plants and the soil.

In general, of the total solar radiation absorbed by the green roof, 27% is reflected, 60% is absorbed by the plants and the soil through evaporation, and only 13% is transmitted into the soil (Eumorfopoulou and Aravantinos, 1998; Kumar and Kaushik, 2005). If the fresh air intake is properly designed, the lower rooftop temperature would also reduce the temperature of the external air that is exchanged with the building's air. Temperatures as low as 25 °C have been observed for the intake air (Peck, *et al.*, 1999).

Usually, the thermal capacity of the green roof is higher than that of the bare roof (Alexandri and Jones, 2008). That is the result not only of the increased thickness of the roof but also of the latent thermal capacity of the damp soil. The air around the leaves of the plants creates an almost still layer of air, which acts as thermal insulation to reduce the thermal transfer from the external air to the building element.

A computer simulation of green roofs indicated that they could improve the thermal performance of a building by blocking solar radiation and reducing daily temperature variations and annual thermal fluctuations (Eumorfopoulou and Aravantinos, 1998) or by reducing heat flux through the roof (Del Barrio, 1998).

4.1.2 Green Roof Energy Performance

Green roofs reduce heat transfer between building and outside environment. Reduction in heat transfer lead to energy savings and cost reduction for the building owner. The energy performance of green roof has been studied in details in Canada (Connelly and Liu, 2005; Liu, 2003; Liu, 2002). The building energy use for space conditioning with a green roof and one with a conventional roof is documented. Each roof has an area of about 35 m^2. It is found that the average daily energy demand for space conditioning due to the heat flow through the conventional roof was 6.0-7.5 kWh/day (for a roof area 35 m^2). However, due to the insulating capacities of the green roof, heat flow was moderated and decreased to less than 1.5 kWh/day (for a roof area 35 m^2), which represented a 75% reduction (Liu, 2003).

In USA, Sonne (2006a & b) and Sonne and Parker (2008) have studied the summer and winter energy performance of a 153 m^2 extensive green roof on a two-storey building. They found that as compared with a conventional flat membrane roof, the green roof can reduce the heat flux by 18% to 50%. In Singapore, a building energy simulation study of a green roof on a 5-storey office building showed annual energy consumption savings of 1% to 15% depending on characteristics of the green roof (Wong, *et al.*, 2003b; Wong, *et al.*, 2002).

Over the entire year, total energy demand is estimated to decrease by 1% with a 0.5% reduction in fall/winter season and a 6% reduction in the spring/summer months (Alcazar and Bass, 2005). Differences in energy savings between warm and cool months is due to the roofs thermal properties. The thermal protection that a green roof offers during the heating period in winter is often negligible. This is because the soil is usually wet and has a high thermal conductivity. Table 4.1 shows typical values of the thermal conductivity of soils.

Table 4.1 Thermal conductivity of soils

Type of soil	**Thermal conductivity, λ ($W.m^{-1}.K^{-1}$)**
Wet soil	2.1
Mixture of soil in wet to damp condition	0.5 to 0.6

Green roofs have a greater potential for reducing heat gain rather than preventing heat loss in the fall and winter. A green roof in Ottawa reduced heat gain by 95 % compared to a heat loss reduction of 26 % (Liu, 2003). Similarly, Del Barrio (1998) noted that green roofs have a greater affinity for preventing heat gain rather than heat loss. Differences in seasonal thermal performance could be due to plant death in the fall and winter months, thereby reducing the amount of heat trapped by the green roof.

In addition, plant coverage, substrate properties are crucial in green roof thermal performance. Results from a study on a green roof in the Mediterranean region noted that soil thickness, density and moisture content all influence roof thermal conductivity (Del Barrio, 1998). Thermal conductivity increases with soil density and decreases with increasing soil moisture content. Thus, selecting light soils with lower density but high field moisture capacity will decrease thermal conductivity.

Other factors also influence the reduction of thermal losses. These are:

(a) The plants reduce the wind strength in proportion to their density and height.
(b) Still air between the evergreen plants and the upper surface of the soil provides additional thermal insulation for the building element.
(c) The biological activity of the plants, known as 'root respiration', prevents the roots from freezing during the winter by keeping the soil temperature higher than the external air.
(d) The thermal capacity of the green roof increases during the winter in contrast to that of the bare roof. This is due to the latent thermal capacity of the wet soil.

4.1.3 Building and Urban Temperatures

With the help of plants and the growing media, green roofs insulate the buildings they cap from the surrounding air temperature and direct solar heat gain, which in turn modifies the internal temperature of the building to the extent that the building can have significant energy savings in cooling and heating. For example, the City of Chicago's 1900 m² test plots show a 10°C difference between the green roof and the nearby black tar roof; the projected avoided energy cost is US$3,600 per year.

Indirect savings may come from the cumulative effect of additional green roofs throughout the city and their effects on ambient outdoor temperature and humidity. If green roofs eventually cover a significant portion of the urban landscape, reduced air temperatures would be expected in the area immediately above and downstream of the green roof. The evaporative cooling can reduce the need for air conditioning by reducing the air temperature immediately adjacent to the building. In Chicago, by 2008, more than 450 green roofs were either in place or under construction in the city, making Chicago the number one green-roofed city in the United States (Source: www.cityofchicago.org).

The general lack of vegetation in existing urban cities is one of the factors affecting the formation of UHI (Alexandri and Jones, 2008). Together with the lowering of building temperatures, green roofs also lower surrounding ambient temperature aided by the evapotranspiration from leaves and the moisture retained in the growing media. A study in Japan showed that the evaporative cooling effect from a roof lawn garden was estimated to have a 50% reduction in the heat flux to surroundings with a temperature difference of 30 ºC (Onmura, Matsumoto, and Hokoi, 2001). The research carried out by researchers at the National University of Singapore showed that the maximum temperature decrease caused by plants was around 30 °C (Wong, *et al.*, 2003a).

4.1.4 Governing Equations

From a thermal modelling point of view, four components can be distinguished in a green roof: the structural part, the soil medium, the canopy (leaf cover) and the air above the roof (Alexandri and Jones, 2007). The heat and mass transfer process of green roof can be described by the governing equations as shown in Table 4.2. The canopy layer is often the most complex part to estimate because the properties of foliage (leaves) could vary significantly and are affected by the surrounding air.

Table 4.2 Heat and mass transfer equations for green roof [adapted from Alexandri and Jones (2007)]

Heat and mass transfer in the structural material
(a) Heat transfer: $\frac{dT}{dt} = a_c \frac{\partial^2 T}{\partial z^2} + \frac{\varepsilon\lambda}{c_c}\frac{\partial q_c}{\partial t}$
(b) Mass transfer: $\frac{dq_c}{dt} = \alpha_m \frac{\partial^2 q_c}{\partial z^2}$
Heat and mass transfer in the air
(a) Heat transfer: $\frac{dT}{dt} = \alpha_a \frac{\partial^2 T}{\partial z^2} + \frac{(h_a - h_b)}{c_{pa}\rho_a} I_1 - \left(\frac{c_1 - c_2}{c_p}\right)\left(D \frac{\partial q_a}{\partial z}\frac{\partial T}{\partial z}\right)$
(b) Mass transfer: $\frac{dq_a}{dt} = D \frac{\partial^2 q_a}{\partial z^2} + \frac{1}{\rho_a} I_1$
Heat and mass transfer in the soil
(a) Heat conduction: $\frac{dT}{dt} = \frac{1}{\rho_g c_G}\frac{\partial}{\partial z}\left(K_s \frac{\partial T}{\partial z}\right)$
(b) Mass transfer: $\frac{d\omega_g}{dt} = \frac{\partial}{\partial z}\left(K_g\left(\frac{\partial \psi_p}{\partial z} + 1\right)\right) = \frac{\partial}{\partial z}\left(D_g \frac{\partial \omega_g}{\partial z} + K_g\right)$
Heat and mass transfer in the canopy
(a) Air temperature: $\frac{dT_a}{dt} = \alpha_a \frac{d^2 T_a}{dz^2} + \frac{1}{r_{aH}}\left.\frac{\partial T}{\partial x}\right\vert_1 - \frac{c_1 - c_2}{c_{pa}} D_a \left.\frac{\partial q_a}{\partial z}\frac{\partial T_a}{\partial z}\right\vert_a$
(b) Vapour diffusion: $\frac{dq_a}{dt} = D_a \frac{d^2 q_a}{dz^2} + \frac{1}{r_a + r_s}\left(e_s(T_1) - e_a\right)$

4.2 Field Studies

Before the measurements were carried out at the green roof sites, visits were made to examine the site conditions and to collect more information to prepare for the measurements. Infrared thermography was used to study the surface temperatures of the roofs and help identify the important performance issues. Weather data were obtained from the Hong Kong Observatory (www.weather.gov.hk) for the same period as the measurements so as to check and compare the climatic conditions. At the St. Bonaventure Catholic Primary School, an automatic weather station has also been set up to monitor the climatic conditions (see Appendix VIII).

4.2.1 Infrared Thermography

The infrared photos of the four green roof sites are given in Appendix IX. Figure 4.2 shows an example of the infrared photo for the APB Centre (4/F). It can be seen that the vegetated area (light blue colour) has much lower temperature than the bare roof or stone pavement. The temperature difference could be as large as 12 °C as shown on the figure. Table 4.3 gives a summary of major characteristics of infrared photos for the four green roof sites.

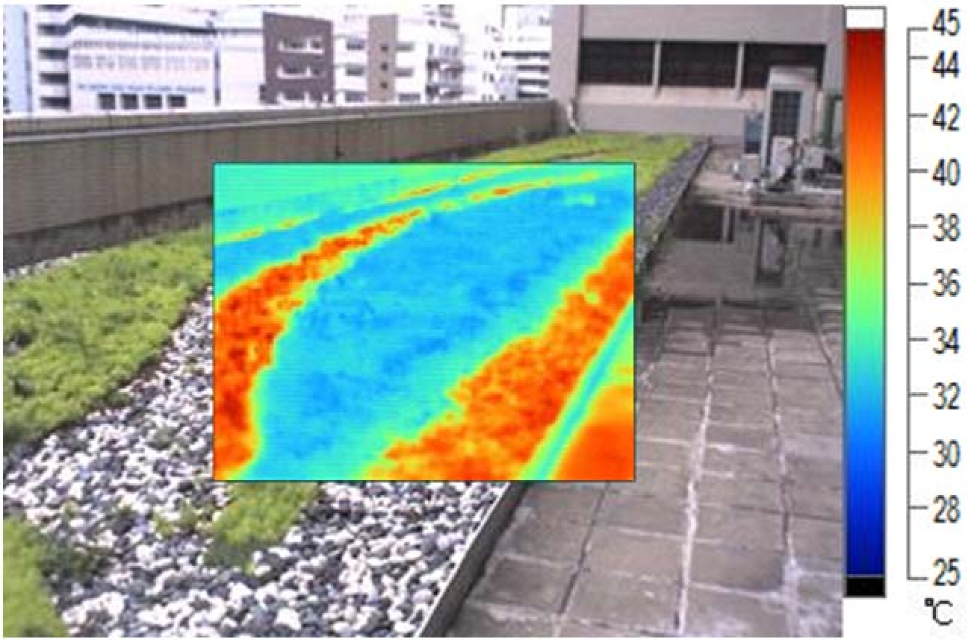


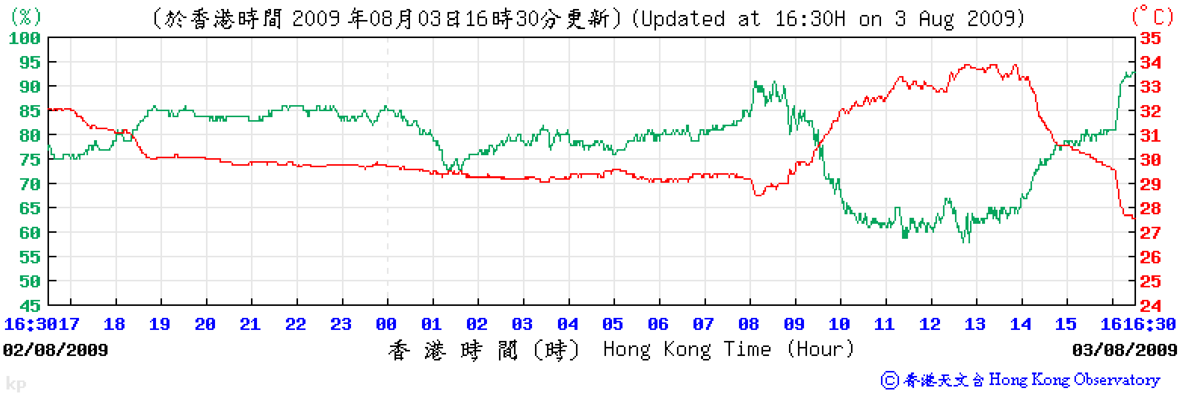
Figure 4.1 Infrared photo of APB Centre at TKW (4/F)

Table 4.3 Summary of major characteristics of infrared photos for green roof sites

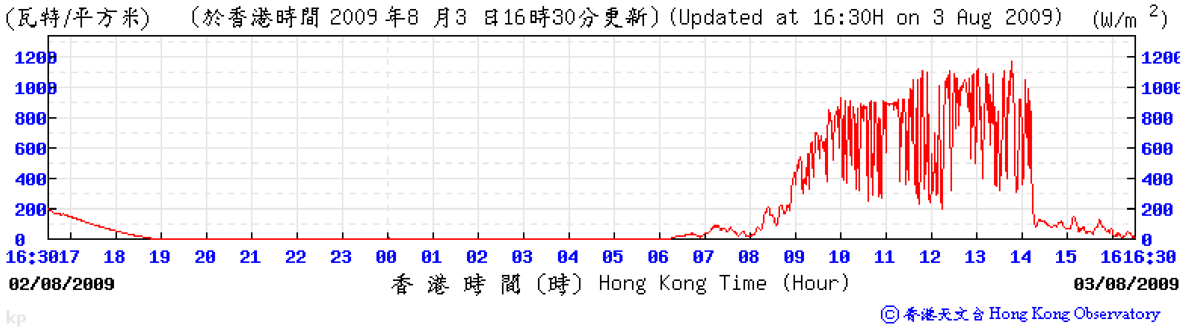
Green roof site	Description
Ngau Tau Kok Municipal Office Building	- Photos taken on 30 Jul 2009 - Surface temperature of green roof = 26 to 32 °C - Surface temperature of bare roof = 33 to 39 °C - Surface temperature of stone pavement = 36 to 39 °C
APB Centre at To Kwa Wan	- Photos taken on 6 Aug 2009 - Surface temperature of green roof = 32 to 34 °C - Surface temperature of bare roof = 40 to 45 °C - Surface temperature of stone pavement = 40 to 45 °C
Yuen Long Government Primary School	- Photos taken on 21 Jul 2009 - Surface temperature of green roof (grass pavement) = 36 to 40 °C - Surface temperature of green roof (planter area) = 32 to 36 °C - Surface temperature of bare roof (control) = 58 to 63 °C
St. Bonaventure Catholic Primary School	- Photos taken on 5 Sep 2009 - Surface temperature of green roof = 40 to 44 °C - Surface temperature of bare roof = 49 to 56 °C - Surface temperature of stone tile pavement = 48 to 55 °C

4.2.2 Weather Conditions

Figure 4.2 shows the examples of weather data obtained from Hong Kong Observatory. The data include dry bulb temperature, relative humidity and horizontal global solar radiation. They could be used to check the climatic conditions when the measurements are being carried out at the green roof sites. Details of the weather data can be found in Appendix X.



(a) Dry bulb temperature and relative humidity (at King's Park weather station)



(b) Horizontal global solar radiation (at King's Park weather station)

Figure 4.2 Examples of weather data from Hong Kong Observatory

4.2.3 Other Observations

It was observed that the soil moisture content at the NTK Building green roof site varied significantly. Figure 4.3 shows the conditions of the green roof during the visits on 15 Jul 2009 and 30 Jul 2009, respectively. The drying of green roof plants and soil will affect the thermal effect. As shown in Figure 4.4, dry soil could have an 'inversion phenomenon' and the substrate temperature measured can exceed the surface temperature of the original exposed roof when the substrate is very dry. Professor Hiroyuki Yamada of the Wakayama University, Japan has investigated this phenomenon and his findings are described below.

The insulating efficiency of "dry" soil is only about 1/3 to that of commonly used insulation materials. But, soil is different in that as its moisture content increases its insulating efficiency also increases. In Figure 4.4, refer to the "100mm DRY Soil" illustration, the heat conducted through dry soil is surprisingly high, thus showing that soil with a poor vegetation cover and low water content does not provide effective thermal resistance. In the "100mm MOIST Soil" diagram, the surface of the moist soil is well-covered with vegetation. A great deal of “latent heat” is reflected off of the surface of the vegetation, and thereby provides good thermal resistance. With moist soil, heat that reaches the soil is reduced to a point where measurable cooling energy savings are realized.

15 Jul 2009 (dry condition)

30 Jul 2009 (with sufficient moisture)

Figure 4.3 Soil moisture of NTK Municipal Office Building

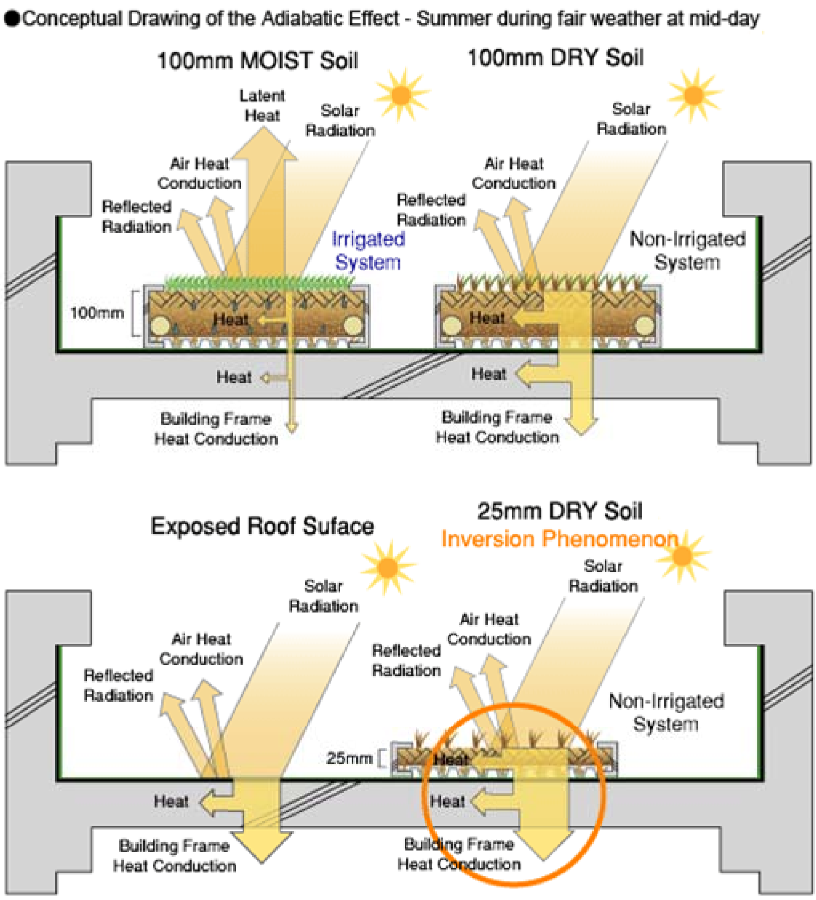


Figure 4.4 Effects of irrigation and soil moisture on thermal effect of green roofs (Source: www.g-sky.com)

The amount of “building frame heat conduction” in the “25mm DRY Soil” and “Exposed Roof Surface” diagrams in Figure 4.4 is virtually identical. This is due to the low water content in the soil which does not provide adequate evaporation to consume heat. Ultra-thin "non-irrigated" soil bases (≤ 25mm) provide no adiabatic effect, poor plant health, poor plant surface coverage and could promote heat conduction into the building. This is called the "Inversion Phenomenon". This is caused by the lack of plant coverage due to "dry" thin soil's inability to support healthy plants. Dark exposed soil has a higher heat conduction value than light coloured concrete, thereby promoting heat into the building.

However, when an ultra-thin system is irrigated, its insulation value is increased significantly (see Figure 4.5). A healthy plant base shades the soil and water evaporation cools the surface. The effectiveness of moisture's cooling effect gradually increases as soil depth increases from 25 mm to 200 mm. Depths above 200 mm provide no further significant increase in the adiabatic effect.

The thickness of a building's roof deck and insulation are also important. On a thick roof deck or with thick insulation (>300 mm), adding a green roof will provides almost no added heat resistance.

In the correct climate, the adiabatic effect of a green roof is significant, and can help reduce the need for air conditioning. However, accurate estimates of energy savings must be made based on the water content of the soil at any given time.

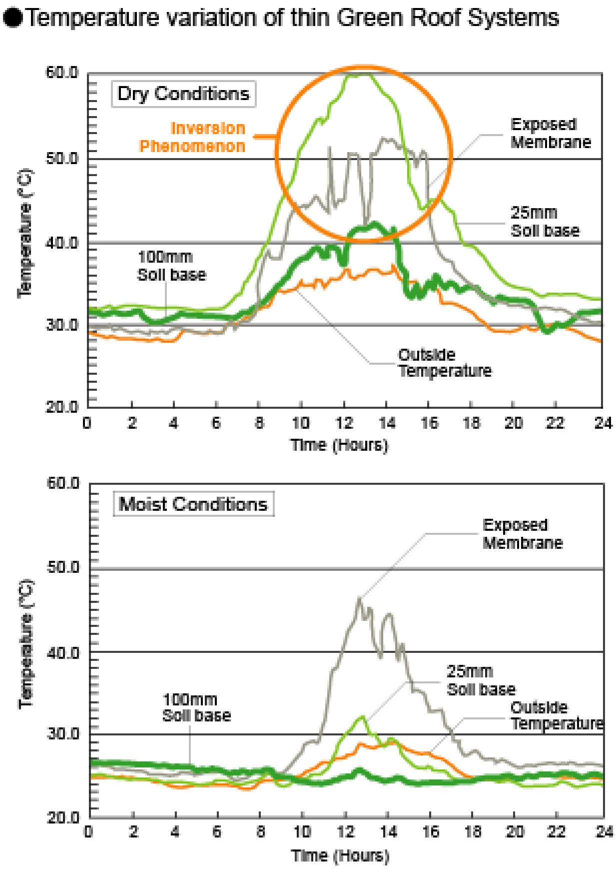


Figure 4.5 Inversion phenomenon and soil moisture of green roofs (Source: www.g-sky.com)

4.3 Green Roof Measurements

The results of green roof measurements are summarized and presented in this section. The key findings of the four green roof sites are explained in Sub-sections 4.3.1 to 4.3.4. A comparison of the temperature profile and heat flux to other research is given in Sub-section 4.3.5. The sensor positions are shown in Appendices V to VIII.

The results for the manual measurements by EMSD subcontractor is described in Sub-section 4.3.6. Further details of these measurements are given in Appendix XI.

4.3.1 Ngau Tau Kok Building

Figure 4.6 shows the temperature variations of the NTK Building over the period 30 Jul-6 Aug 2009. These are the data for the middle part of the green roof that has short plants (see the photos in Figure 3.1 and Appendix V). It can be seen that the bare roof (Ch4-control on walkway) has large daily temperature fluctuations (diurnal difference up to 25 °C). The roof surface under the vegetation (Ch1-Bed_bottom) has much smaller daily fluctuations (only up to 10 °C). The temperatures measured in middle of the growing medium (Ch2-Soil_middle) and at the canopy (Ch3-Plant_Surface) lie between the two extremes (Ch4 & Ch1).

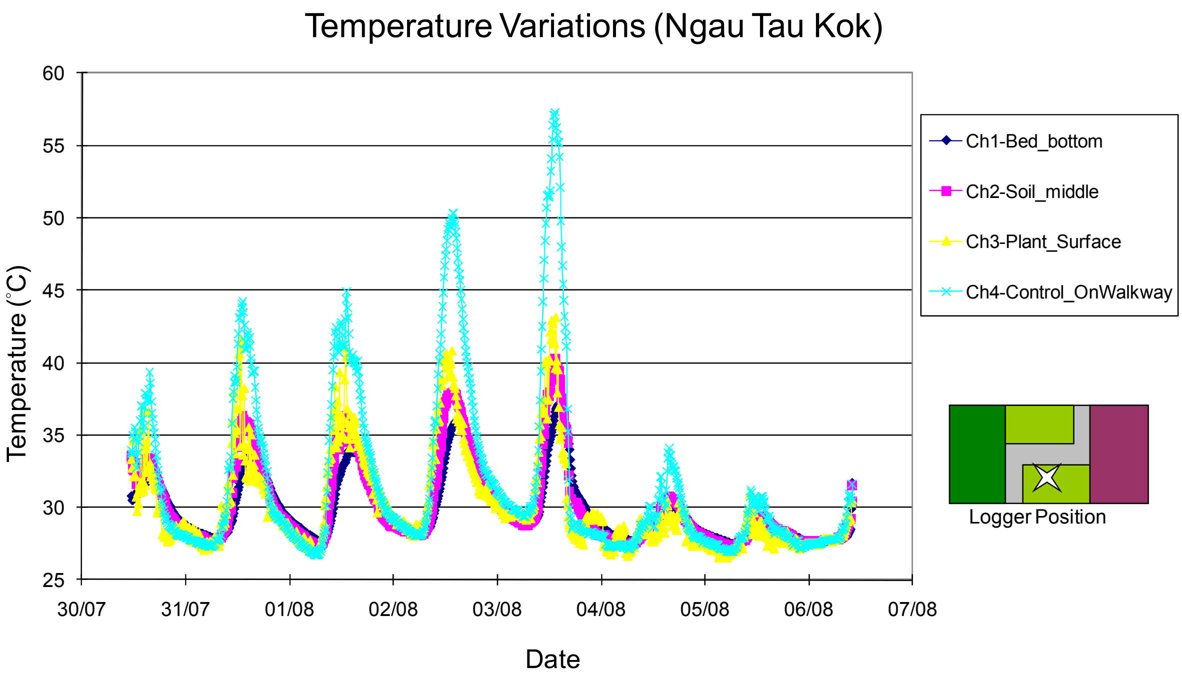


Figure 4.6 Temperature of NTK Building: middle part, short plants, 30 Jul-6 Aug 2009

Figure 4.7 shows the temperature variations of the NTK Building over the period 30 Jul-6 Aug 2009 for the taller plants (the purple zone). As compared with Figure 4.6, the temperature fluctuation is smaller because of the effect of better shading and evapotranspiration in the taller plants.

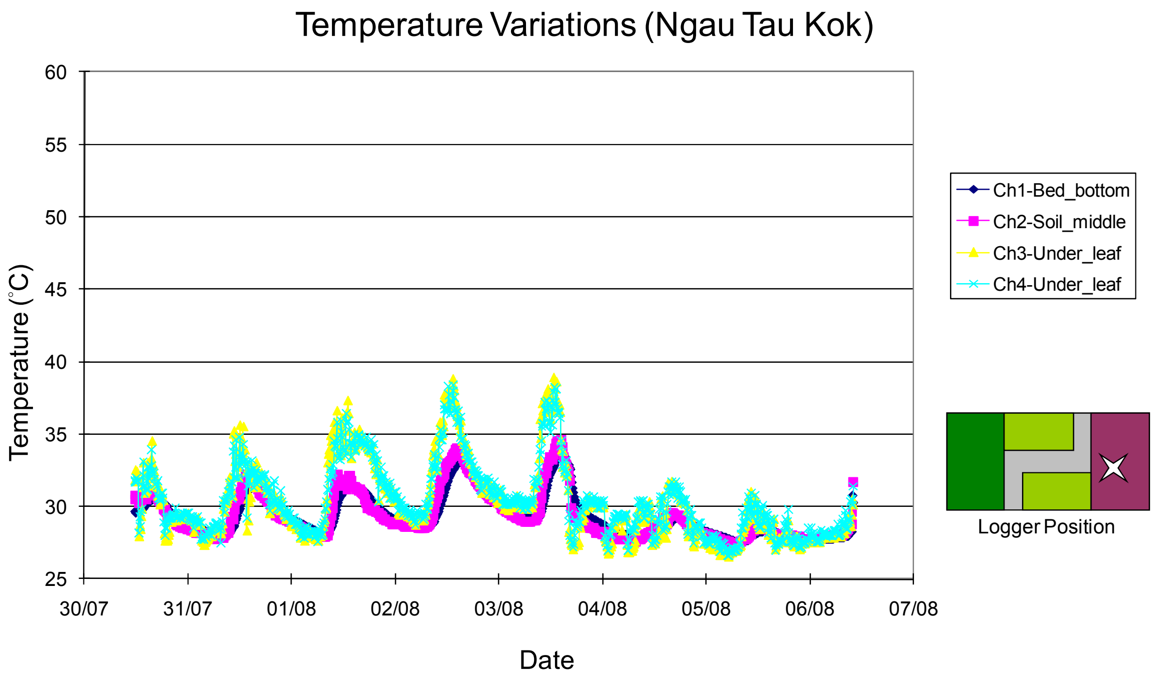


Figure 4.7 Temperature NTK Building: taller plants, 30 Jul-6 Aug 2009

The 24-hour temperature profiles of the NTK Building for 3 August 2009 which is the hottest day over the period 30 Jul-6 Aug 2009 are shown in Figures 4.8 (short plants) and 4.9 (taller plants). The shading effect of the taller plants is also quite obvious. The daytime variation (07:00-19:00) is quite large. During the night time, the temperatures at different layers are quite close to each other. This implies that the cooling effect of the green roof diminishes at night time.

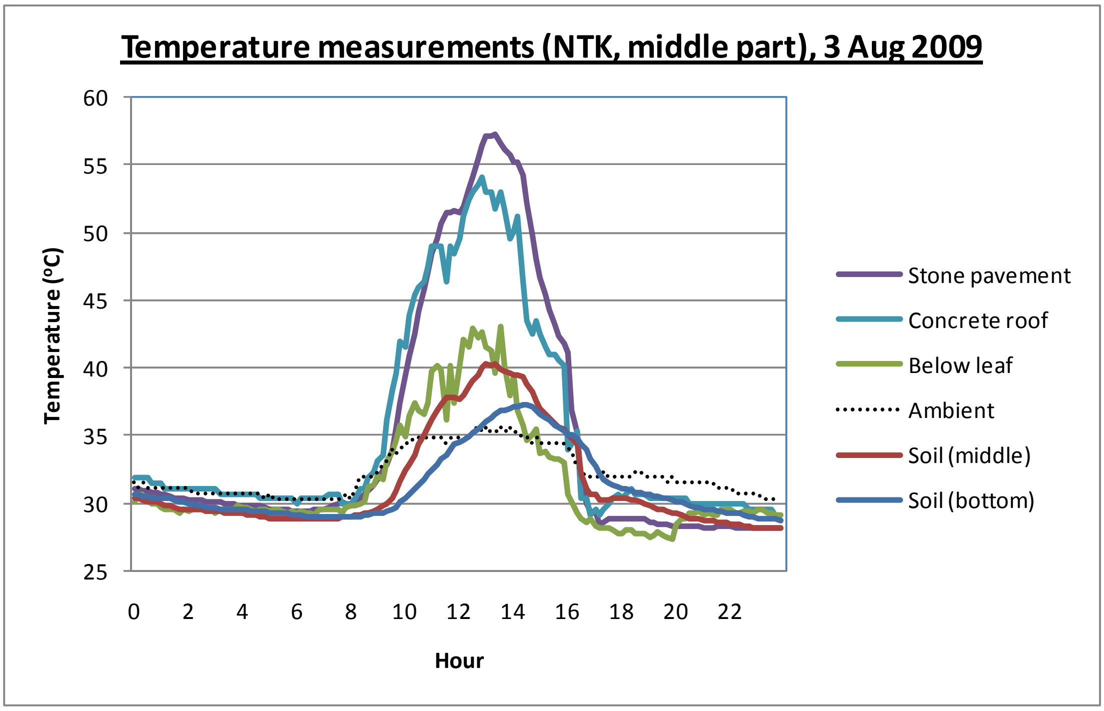


Figure 4.8 Temperature of NTK Building: middle part, short plants, 3 Aug 2009

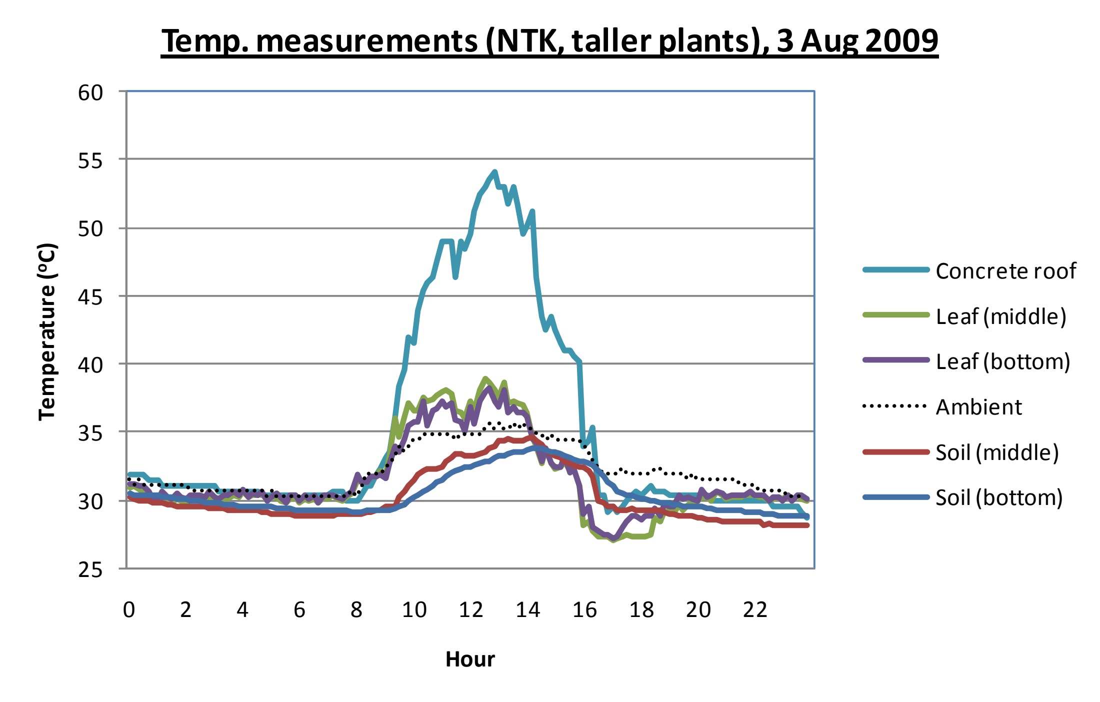


Figure 4.9 Temperature of NTK Building: taller plants, 3 Aug 2009

4.3.2 APB Centre

Figure 4.10 shows the 24-hour temperature profiles for the hottest day (8 Aug) of APB Centre 4/F during the measurement period. It can be seen that the bare concrete roof and soil bottom have temperature fluctuations of 13 °C and 3 °C, respectively. The temperatures measured at the ceilings under the concrete roof and green roof are shown in Figure 4.11. A temperature difference of about 0.5 to 1.5 °C is found.

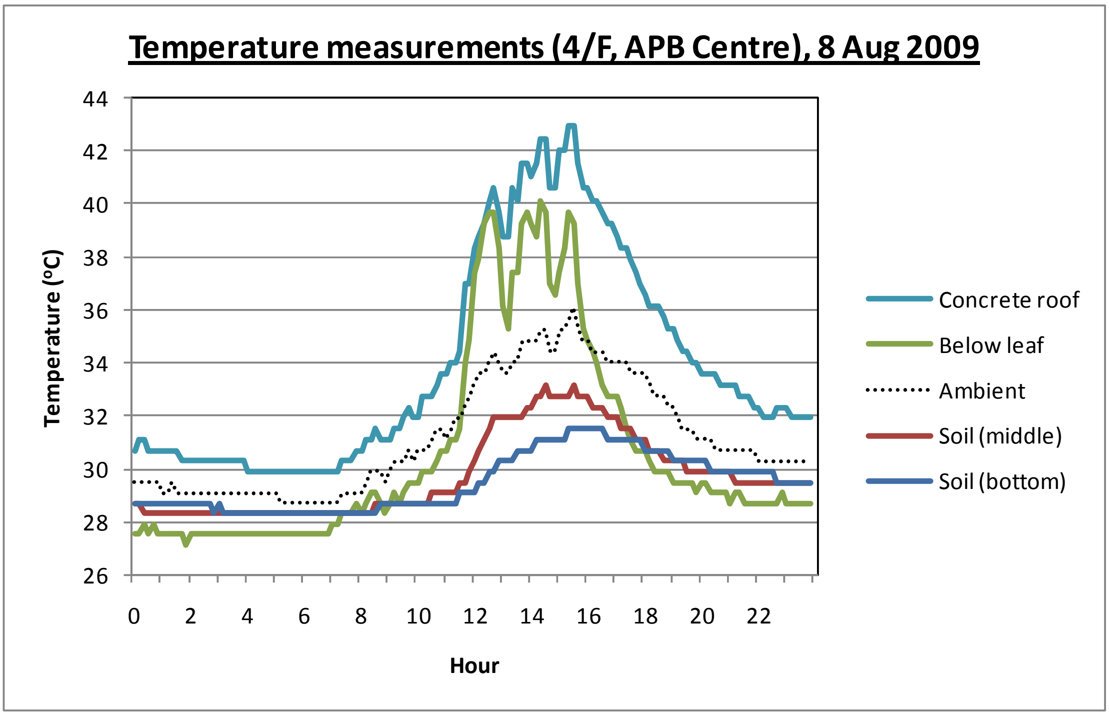


Figure 4.10 Temperature data of APB Centre 4/F, 8 Aug 2009

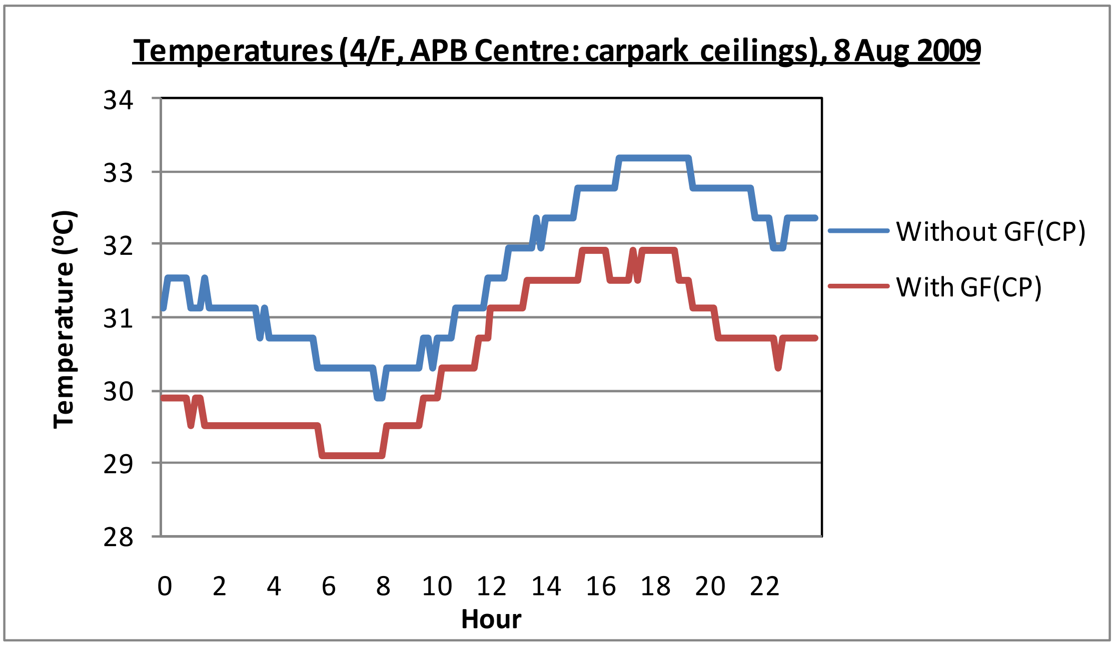


Figure 4.11 Temperature data of APB Centre 4/F for carpark ceilings, 8 Aug 2009

4.3.3 Yuen Long Government Primary School

Figures 4.12 and 4.13 show the temperature data of YLGPS on the hottest day (16 Aug 2009) during the measurement period for the pavement grass area and planter area, respectively (see Appendix VII). It can be seen that the planter area has much smaller temperature fluctuations and the soil temperatures are maintained quite stable at about 30 °C throughout the day.

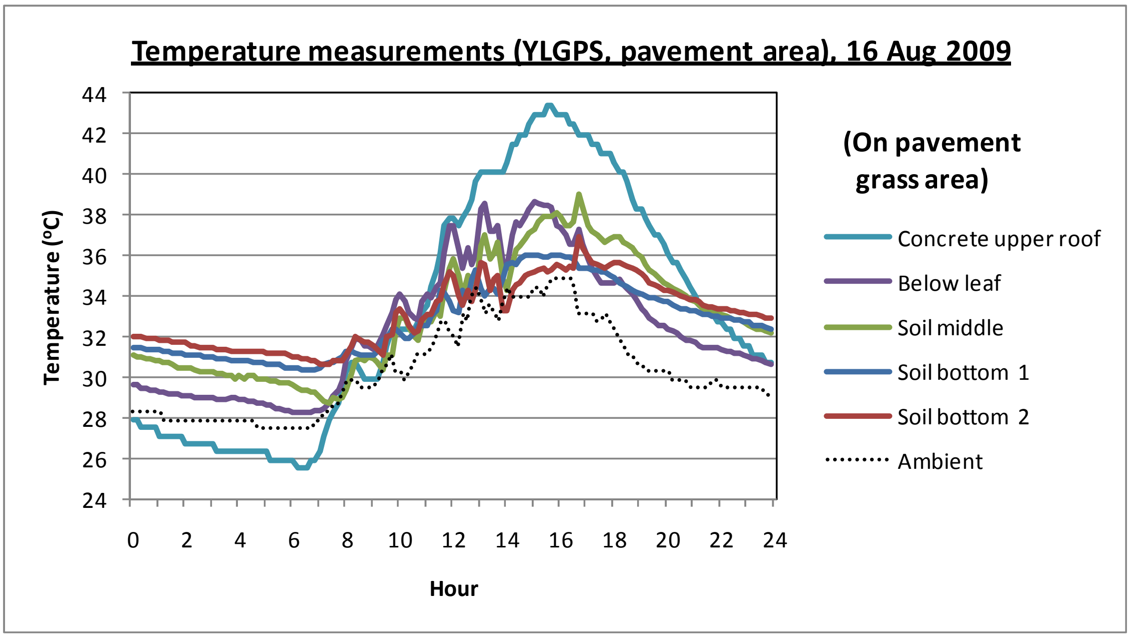


Figure 4.12 Temperature data of YLGPS (on pavement grass area), 16 Aug 2009

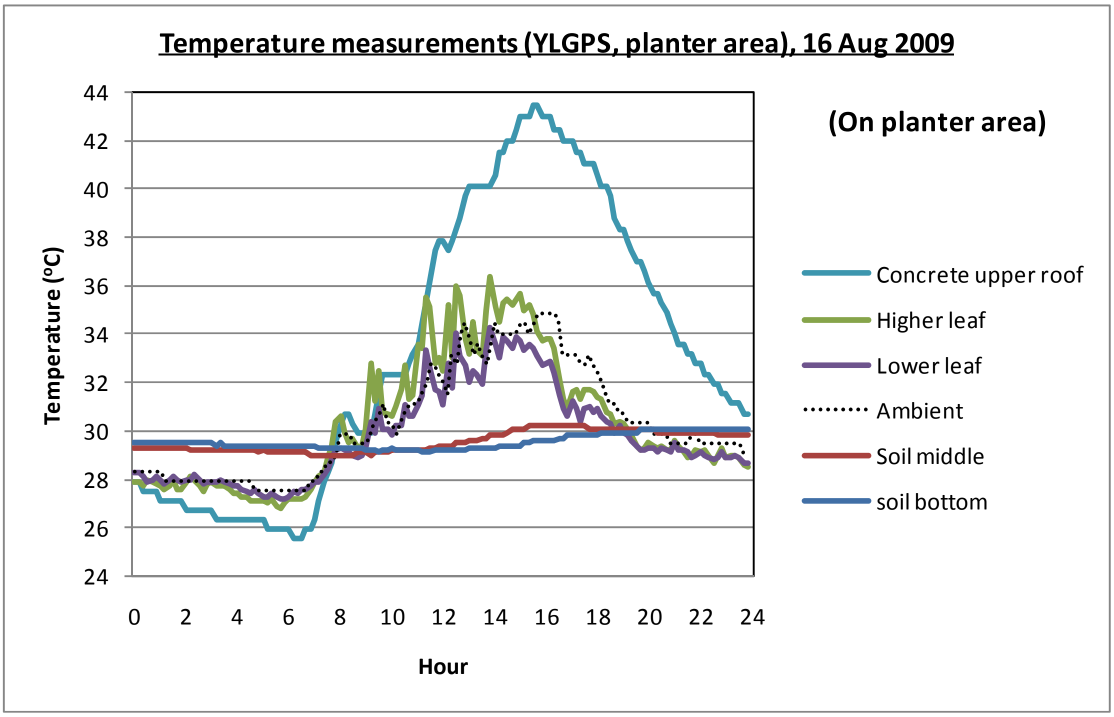
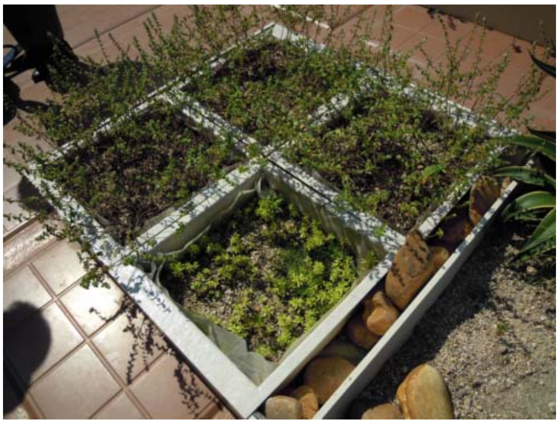


Figure 4.13 Temperature data of YLGPS (on planter area), 16 Aug 2009

4.3.4 St. Bonaventure Catholic Primary School

For SBCPS, research was developed by HKU to investigate very-light-weight green roof, effect of urban farming on green roofs and the thermal effect of a fabric glass insulation panel. Figure 4.14 shows the materials on the roof. The urban farming is carried out using fabric glass boxes (each 500 mm x 500 mm) and herbal plants are grown with a canopy height of about 300 mm (see Appendix VIII for details).

Green roof and insulation panel (orange)



Urban farming boxes with herbal plants

Figure 4.14 Green roof, insulation panel and urban farming boxes of SBCPS

Figure 4.15 shows the temperature variations of the SBCPS over the period 5-12 Sep 2009. Similar to other sites, the daily temperature fluctuation of the non-green roof is large (up to 40 °C difference measured at the insulation panel). The thermal effects of the very-light-weight extensive green roof and the area of urban farming (with thicker soil and taller plants) were studied. Figure 4.16 shows the 24-hour temperature profiles for the hottest day (8 Sep). It can be seen from the two figures that the extensive green roof has smaller insulating effect than the urban farming area, but it can help reduce the weight significantly on the roof.

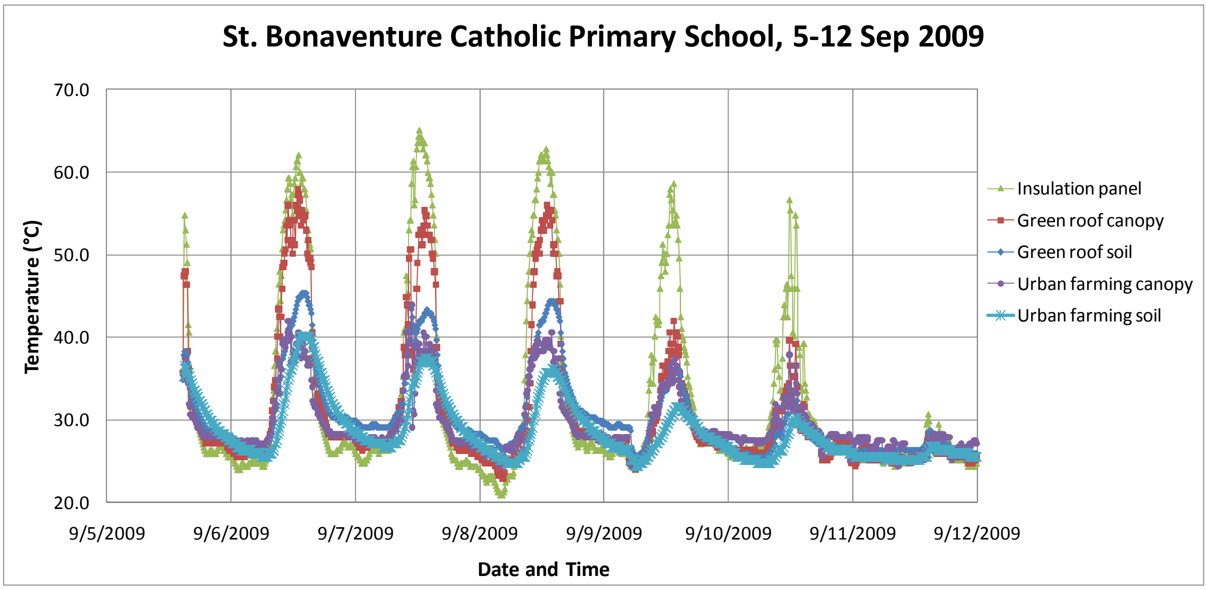


Figure 4.15 Temperature data of SBCPS, 5-12 Sep 2009

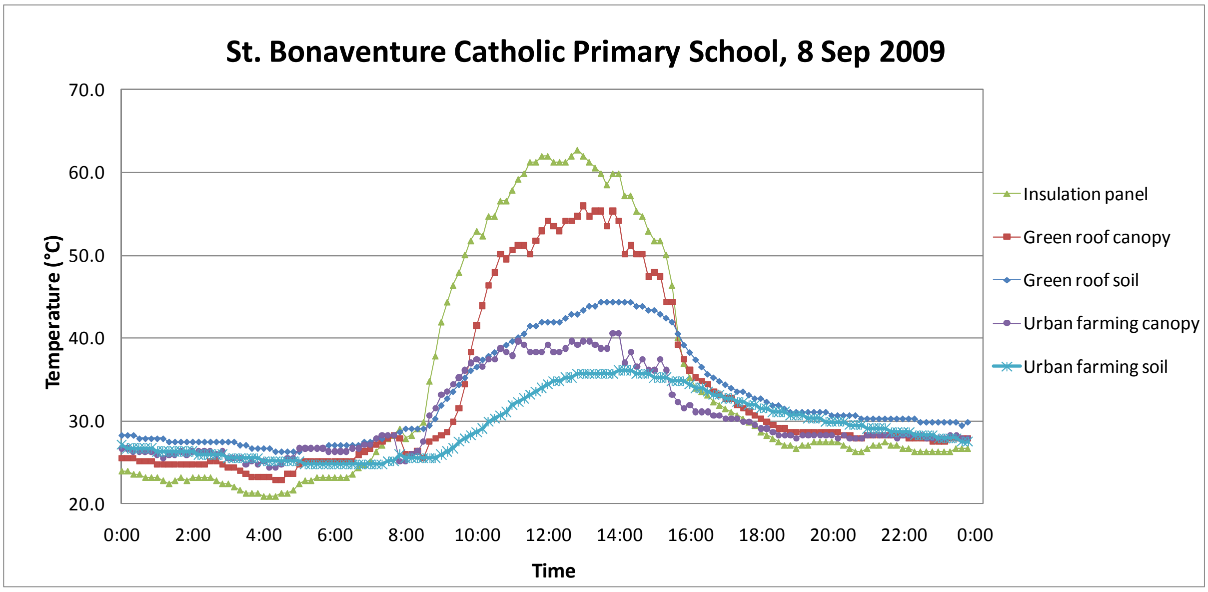


Figure 4.16 Temperature data of SBCPS, 8 Sep 2009

As shown on Figure 4.16, because of larger thermal storage capacity of the soil in the urban farming area, its temperature during the night time is slightly higher than that of the extensive green roof.

4.3.5 Temperature Profile and Heat Flux

Table 4.4 shows a summary of the daily temperature fluctuations on the respective hottest day for the four green roof sites. Although the dates and locations of the measurements are different, the general patterns and trends of the daily temperatures are similar. The information can give us an indication of the thermal effect for the different green roof designs and situations.

Table 4.4 Daily temperature fluctuations at the green roof sites

Site	Date	Daily temperature fluctuation (°C) (daily maximum temperature – daily minimum temperature)			
		Ambient	Bare roof	Green roof (short plants)	Green roof (taller plants)
Ngau Tau Kok (NTK) Building	3 Aug 2009	5.4 (35.7 – 30.3)	25.4 (54.1 – 28.7)	8.5 (37.2 – 28.7)	7.0 (33.8 – 28.8)
APB Centre 4/F	8 Aug 2009	7.4 (36.1 – 28.7)	13.6 (42.9 – 29.9)	3.2 (31.5 – 28.3)	N/A
Yuen Long Govt Primary School	16 Aug 2009	7.3 (34.8 – 27.5)	17.8 (43.4 – 25.6)	5.6 (36.0 – 30.4)	1.0 (30.1 – 29.1)
St. Bonaventure Catholic Primary School	8 Sep 2009	7.7 (34.0 – 26.3)	31.3 (55.8 – 24.5)	18.1 (44.4 – 26.3)	11.3 (36.1 – 24.8)

Note: For Yuen Long Government Primary School, short plants refer to the pavement grass area; taller plants refer to the planter area. For St. Bonaventure Catholic Primary School, short plants refer to the sedum light weight extensive green roof; taller plants refer to the urban farming box.

The temperature profiles described in the previous sub-sections could be compared with those from other research studies overseas. Figures 4.17 and 4.18 show respectively temperature profile and heat flux on a summer day for a green roof research in Canada (Liu, 2003). Similar to our findings, the green roof can help stablise the temperature fluctuation and reduce the heat flow into the building.

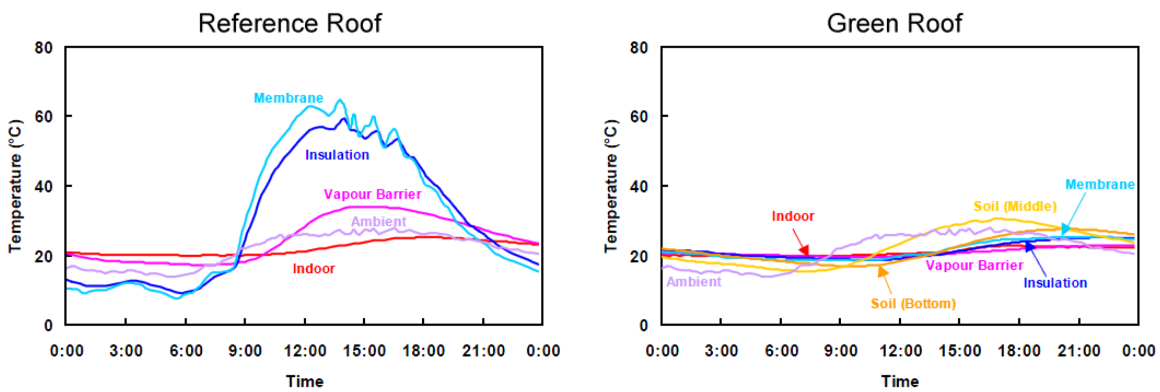


Figure 4.17 Temperature profile on a summer day (16 Jul 2001) [Source: Liu (2003)]

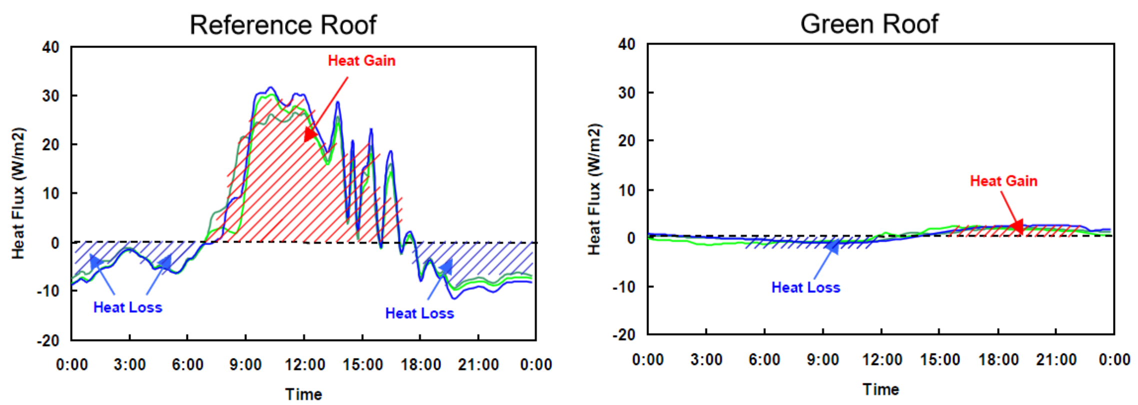


Figure 4.18 Heat flux on a summer day (16 Jul 2001) [Source: Liu (2003)]

4.3.6 Manual Temperature Measurements by EMSD Subcontractor

The data and information of the manual measurements by EMSD subcontractor were examined. Graphs are plotted to show the temperature variations; the details are given in Appendix XI. To compare these data with the temperatures measured by the HKU researchers using data loggers, the corresponding graphs of the HKU data for the respective days of the measurements are plotted and shown in Appendix XI. It is found that the general patterns of the temperature variations on the roof surfaces are similar but the absolute values might not be the same since the manual measurements have taken the average of several points at different positions on the roof.

It is interesting to note that the manual temperature data for the building interior (floor slab and ceiling void) vary only little amount as compared to that of the roof surfaces. As mentioned in Sub-section 2.2.2, for the heat transfer of roof elements, if the roof is very well insulated or if there is a ventilated space between the roof surface and the building interior, then adding a green roof will provide no further significant increase in thermal resistance. This might help explain the phenomenon in this manual measurement results. In fact, not only the manual data could explain this phenomenon, some of the actual data of the temperature loggers also indicate such findings (see Appendices V, VI and VII).

Since the manual measurements were done only for daytime hours from 08:30 to 18:30, no information about the night time conditions can be obtained to analyse the 24-hour temperature profile.

4.4 Thermal and Energy Models

Based on a steady-state Fourier theory in one dimension, the thermal behaviour of green roof can be assessed. The dynamic thermal response of green roof can also be evaluated using computer-based simulation methods on green roof models.

4.4.1 U-value Calculations

As mentioned in Section 3.3, the contribution of a green roof to the thermal protection of buildings can be evaluated by studying the U-value of the roof construction. The green roof can contribute to the improvement of the U-value and the reduction of thermal gains/losses (Eumorfopoulou and Aravantinos, 1998). Table 4.5 shows a summary of the major results of the U-value calculations for the four green roof sites; the details of calculations can be found in Appendix XII.

As shown in Table 4.5, the contribution of the green roofs varied from 16% (10/F of APB Centre) to 42% (Yuen Long Government Primary School), depending on the soil thickness and roof construction. It should be noted that the choice of materials in the planted part of the roof does not greatly influence the thermal behaviour of a thermally insulated roof. But when the roof is not thermally insulated, the influence will be more significant. Niachou, *et al.* (2001) conducted a measurement of surface and air temperatures on green roofs to examine their thermal properties and potential energy savings. They analysed the effect of green roofs with different levels of insulation and showed reductions in energy consumption ranging from 40% for the non-insulated roof to 2% for the well insulated roof.

Table 4.5 Major results of U-value calculations

Ref.	Description*	U-value (W/m^2.K)	% Change**
1	NTK Building -- bare roof	2.433	
	NTK Building -- green roof 100 mm soil & short plants	1.772	- 27.2%
	NTK Building -- green roof 150 mm soil & taller plants	1.646	- 32.4%
2a	APB Centre, 4/F – bare roof	1.228	
	APB Centre, 4/F -- green roof 100 mm soil & sedum plants	1.020	- 16.9%
2b	APB Centre, 10/F -- bare roof	1.194	
	APB Centre, 10/F -- green roof 100 mm soil & sedum plants	0.997	- 16.5%
3	YLGPS -- bare roof	2.166	
	YLGPS -- green roof, pavement area, 92 mm soil & grass	1.701	- 21.5%
	YLGPS -- green roof, planter area 350 mm soil & tall plants	1.248	- 42.4%
4	SBCPS -- bare roof	2.830	
	SBCPS -- green roof (very light weight) 50 mm soil	2.069	- 26.9%

Note: * Building roof is included in the calculation of U-values for different types of green roofs
** % Change = percentage change of U-value as compared to the respective bare roof

For the case of SBCPS, calculations have been done for three additional cases: i) urban farming box, ii) insulation panel and iii) both of them. The results are shown in Table 4.6. It is found that with the additional insulation panel, the U-value is significantly reduced. At the same time, the temperature data (see Figures 4.14 and 4.15) indicated a more effective thermal protection by the plants of urban farming.

Table 4.6 U-value calculations for SBCPS with urban farming and insulation panel

Ref.	Description*	U-value (W/m^2.K)	% Change**
4	SBCPS -- bare roof	2.830	
	SBCPS -- green roof (very light weight)	2.069	- 26.9%
i)	SBCPS -- green roof (urban farming box on bare roof)	1.439	- 49.2%
ii)	SBCPS -- bare roof + fabric glass insulation panel	0.739	- 73.9%
iii)	SBCPS -- green roof (urban farming box on insulation panel)	0.590	- 79.2%

Note: * Building roof is included in the calculation of U-values for different types of green roofs
** % Change = percentage change as compared to the respective bare roof

4.4.2 Roof-Envelope Ratio

The relative importance of the roof thermal envelope load depends on the roof area and construction, as well as the amount of building internal loads. Martens, Bass and Alcazar (2008) have studied the roof-envelope ratio impact on green roof energy performance and indicated that the total energy savings of a green-roofed building over a conventional roofed building were far more significant for single-storey structures. For a building in Toronto with 250×250 m green-roof design and 50,000 W internal loading, the percentage of energy savings was found to be 73%, 29%, and 18%, for a one, two, and three-storey design, respectively. This result is similar to Hui (2004) who has studied the thermal benefits of green roof on a two-storey construction site office located in Tsing Yi (see Sub-section 2.3.4).

Since Hong Kong has many high-rise buildings with limited roof areas, it is expected that the contribution of green roof to the energy conservation of these high-rise buildings as a whole is not very large. To study how the roof-envelope ratio affects the relative importance of roof thermal load, a building energy simulation model was set up and computations were performed using the Energy-10 simulation software (www.energy-10.com) developed by the National Renewable Energy Laboratory (NREL) in USA. Details of the simulation model and results are given in Appendix XIII. The simulation model is a hypothetical square office building with a typical floor of 40.8 m (width) x 40.8 m (length) and a floor-to-floor height of 3.4 m. For sake of easy comparison, this base case model building is assumed to have the same bare roof U-value as the NTK Building.

From the calculations in Appendix XIII, it is found that for the topmost floor of the building, the roof thermal load constitutes 15.3% and 24.3% of building electrical energy consumption and building electrical peak demand, respectively. If the building has multiple storeys, then these percentage figures will decrease accordingly. Figure 4.19 shows the effects of roof-envelope ratio and number of storeys on percentage of roof to building total electrical energy. It can be seen that the relative impact of the roof thermal load decreases significantly for high-rise buildings. For 10-storey, 20-storey and 30-storey buildings, the percentage of roof load to whole building total electrical energy are only 1.8%, 0.9% and 0.6%, respectively (see Figure 4.19). Therefore, even if a green roof can reduce the roof thermal load significantly, the overall impact on the whole building energy consumption (the direct effect) is not large for high-rise buildings. However, the indirect effect to urban temperature would be essential when a large scale greening is adopted.

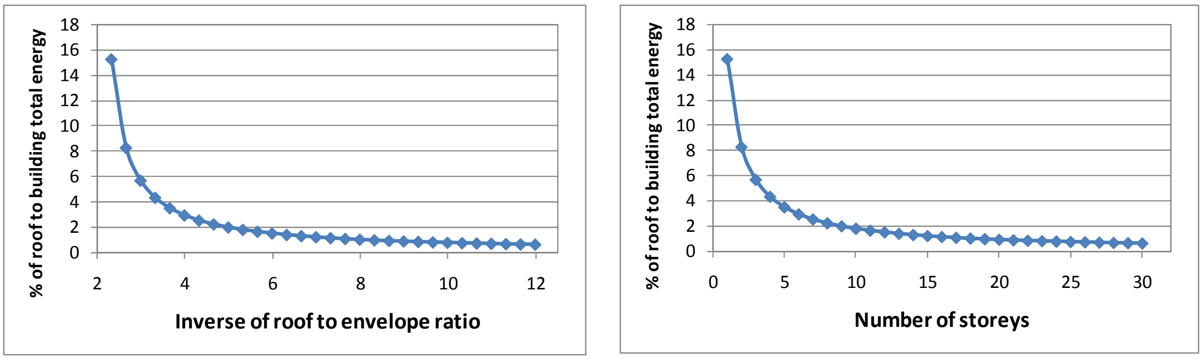


Figure 4.19 Effects of roof-envelope ratio and number of storeys on percentage of roof to building total energy

Nevertheless, although the contribution of green roofs to the thermal protection of buildings may be small, they are, however, both energy-efficient and ecologically acceptable, and are recommended whenever practicable (Eumorfopoulou and Aravantinos, 1998). For Hong Kong, it is usually more effective to apply green roofs to the top of building podiums and medium- or low-rise buildings/structures (Hui and Chan, 2008).

4.4.3 Roof U-value and Building Energy Performance

As shown in Tables 4.5 and 4.6, the roof U-value of the green roof sites varies from

0.59 to 2.83 W/m^2.K. To evaluate how the roof U-value affects the building energy performance, investigations were conducted using the Energy-10 building energy simulation model as mentioned in Sub-section 4.4.2. The roof U-values in Tables 4.5 and 4.6 were applied to the model (for the whole roof) and the correlations with the following parameters were determined from the simulation results.

(a) Annual total building electrical energy use (thousands GJ)
(b) Peak electricity demand (kW)

Figures 4.20 and 4.21 shows the correlations of the two parameters with the roof U-value. The respective linear regression equations are also indicated. Details of the calculations can be found in Appendix XIII.

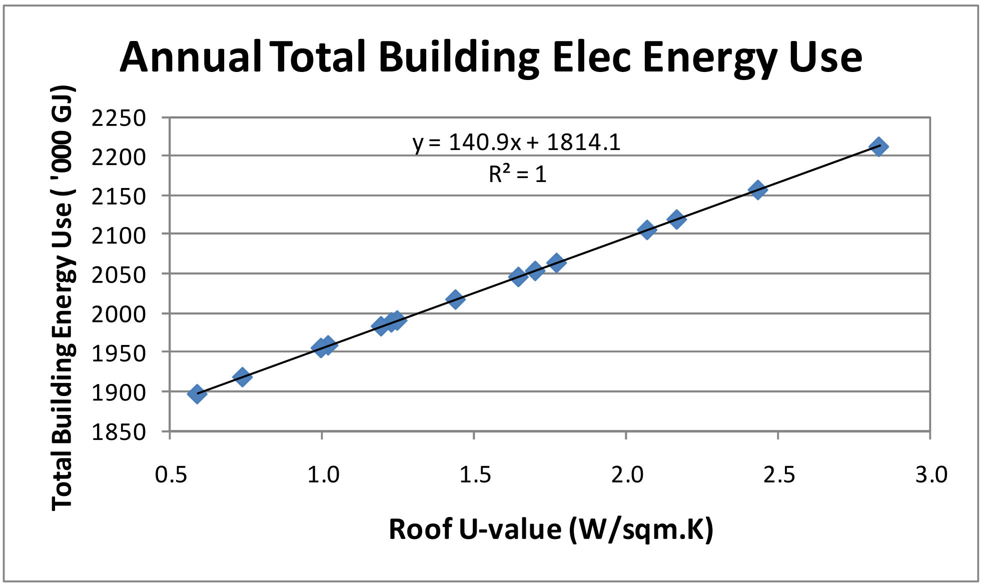


Figure 4.20 Annual total building electrical energy and roof U-value

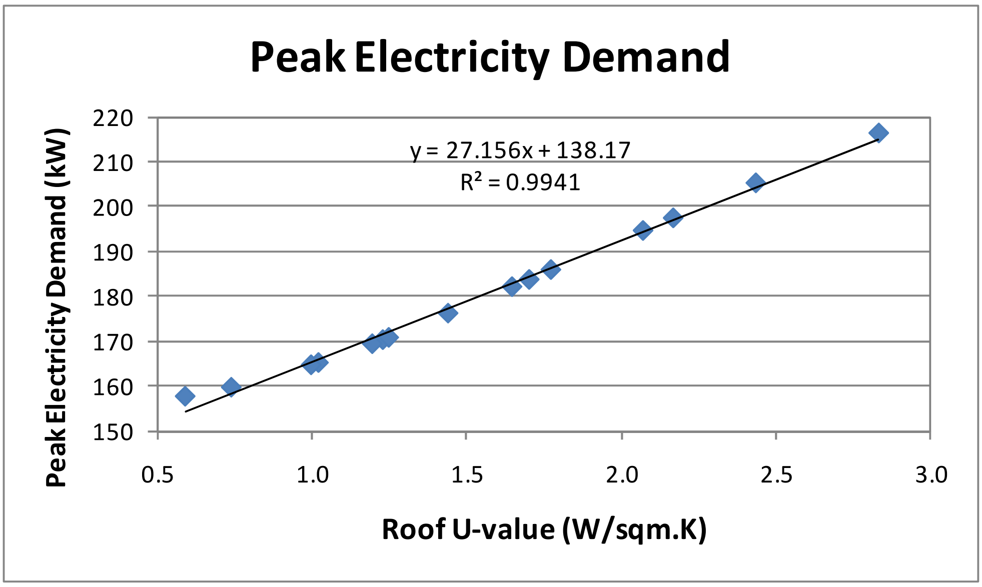


Figure 4.21 Peak electricity demand and roof U-value

Based on the assessment of U-value and the linear regression equation in Figure 4.20, a rough estimation of the effects of green roofs for the four green roof sites is done and given in Appendix XIV. The results indicate that when the percentage of green roof area is taken into account, the reduction of the U-value of the whole roof slab is from 1.4% (10/F of APB Centre) to 31.9% (Yuen Long Government Primary School). The corresponding percentage saving of annual total building electrical energy (for top floor only) would range from 0.1% (10/F of APB Centre) to 4.6% (Yuen Long Government Primary School). When more floors are considered, these figures will be reduced further. This again shows that the contribution of such small green roofs to the thermal protection of the whole multi-storey building is not large.

4.4.4 Generalised Thermal and Energy Performance

The thermal and energy performance of adding a green roof to a bare roof can be studied generally by assessing the thermal resistance of green roofs and the effects on different types of roof structures. Table 4.7 shows the thermal resistance values of green roofs taken for the four project sites; the thermal resistance of the fabric glass insulation panel in SBCPS is also given for comparison.

Table 4.7 Thermal resistance of green roofs

Ref.	Description*	Thermal resistance (m^2.K/W)
1	NTK Building -- green roof 100 mm soil & short plants	0.154
	NTK Building -- green roof 150 mm soil & taller plants	0.197
2a	APB Centre, 4/F -- green roof 100 mm soil & sedum plants	0.166
2b	APB Centre, 10/F -- green roof 100 mm soil & sedum plants	0.166
3	YLGPS -- green roof, pavement area, 92 mm soil & grass	0.155
	YLGPS -- green roof, planter area 350 mm soil & tall plants	0.369
4	SBCPS -- green roof (very light weight) 50 mm soil	0.130
4 i)	SBCPS -- green roof (urban farming box)	0.342
	* The following data is shown for comparison:	
4 ii)	SBCPS -- fabric glass insulation panel	1.000
4 iii)	SBCPS -- urban farming box + insulation panel	1.342

It can be seen from Table 4.7 that the thermal resistance of the green roofs varies from 0.13 to 0.37 m^2.K/W. With this range in mind, analysis was carried out to study the effects of adding green roof to the bare roof. The percentage change of the roof U-value (indicates the thermal performance) and the percentage change of annual total building electrical energy use (indicates the energy performance) were calculated in Appendix XIV. Figures 4.22 and 4.23 show the key analysis results. The linear regression equation on Figure 4.20 was used to estimate the total building electrical energy use (for a typical single-storey office building) from the overall roof U-value. Using these two graphs, the effects of adding green roof can be estimated, by checking the U-value of bare roof and the R-value of green roof.

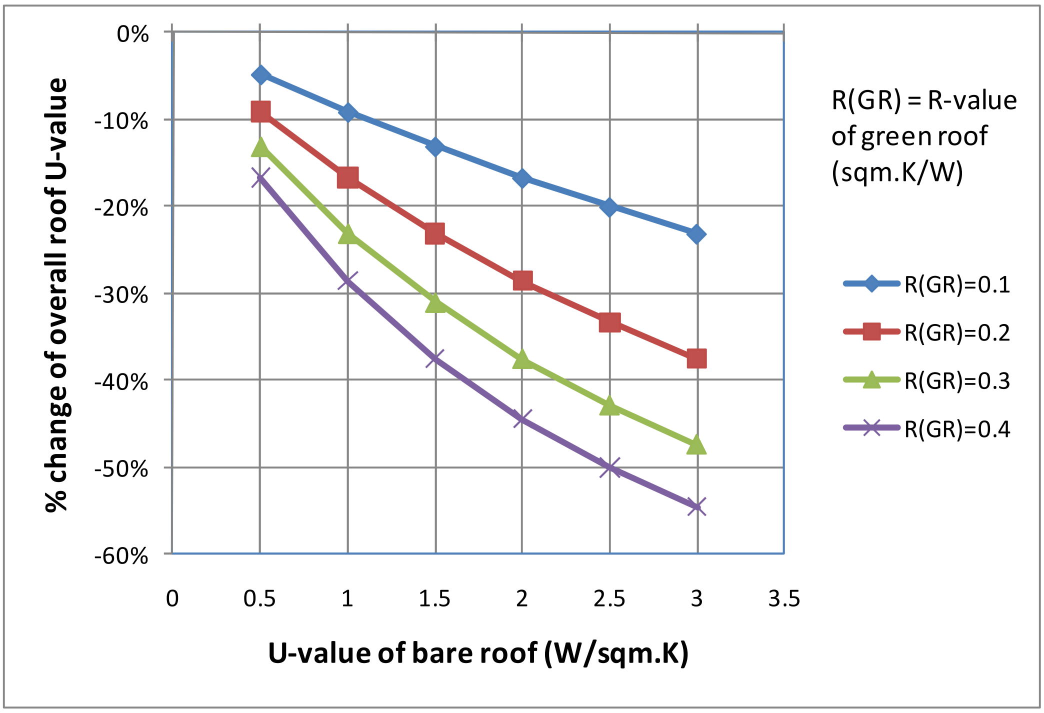


Figure 4.22 Effect of adding green roof on overall roof U-value

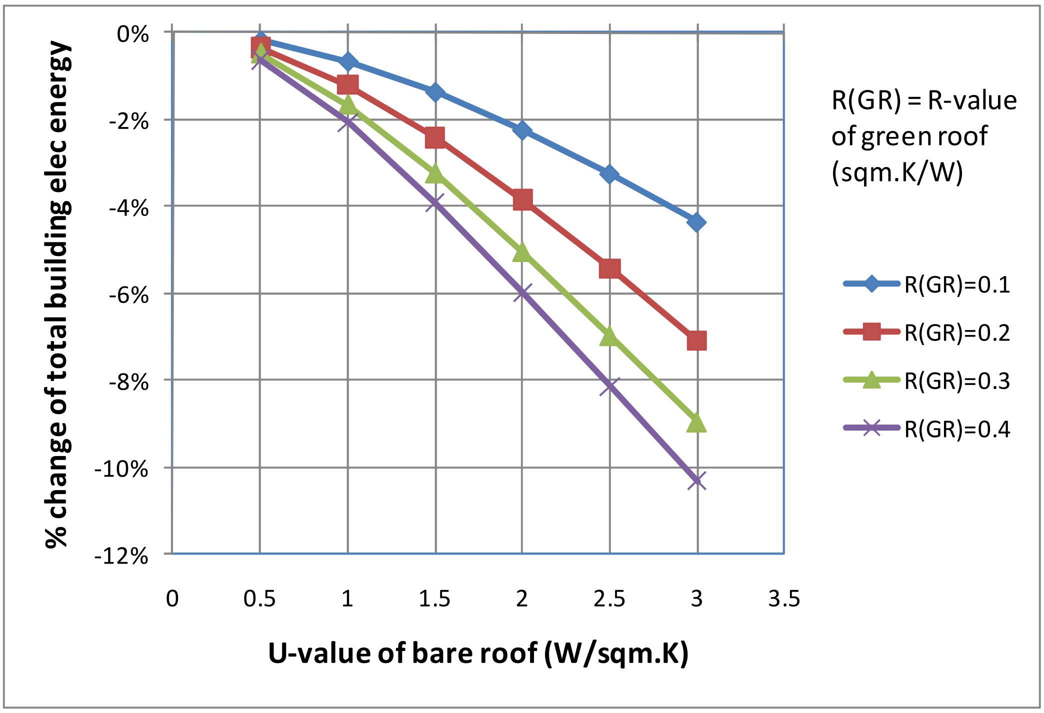


Figure 4.23 Effect of adding green roof on total building electrical energy use

Figure 4.23 is valid for the typical single-storey office building defined in Appendix XIII. When it is changed to a multi-storey building or when the green roof only constitutes a portion of the roof area, then the roof-envelope ratio can be applied (see Figure 4.19) to determine the percentage of roof to building total energy. It should be noted that the U-value calculations here have ignored the thermal resistance of the canopy plant layer and the indirect effect of heat transfer from the green roof to the surrounding environment. More detailed simulation models will be needed if these factors are to be considered carefully.

4.4.5 Green Roof Simulation Models

In recent years, computer-based simulation models for green roofs have been developed in some energy software tools to facilitate the assessment of green roof energy performance in green or sustainable building design. Table 4.8 shows three examples of the software and related research papers.

Table 4.8 Green roof models and energy simulation software

Reference	Paper Title	Software
Lazzarin, Castellotti and Busato (2005)	Experimental measurements and numerical modelling of a green roof	TRNSYS
Martens, Bass and Alcazar (2008)	Roof-envelope ratio impact on green roof energy performance	ESP-r
Sailor (2008)	A green roof model for building energy simulation programs	EnergyPlus

Usually the green roof models take into account the following aspects (see also Section 2.3):

- Long wave and short wave radiative exchange within the plant canopy
- Plant canopy effects on convective heat transfer
- Evapotranspiration from the soil and plants
- Heat conduction (and storage) in the soil layer

As with a traditional roof, the energy balance of a green roof is dominated by radiative heat from the sun. This solar radiation is balanced by sensible (convection) and latent (evaporative) heat flux from soil and plant surfaces combined with conduction of heat into the soil substrate. This energy balance is illustrated in Figure 4.24. Often, the simulation model or module allows the user to specify green roof as the outer layer of a rooftop construction. The user can then specify various aspects of the green roof design including growing media depth, thermal properties, plant canopy density, plant height, stomatal conductance (ability to transpire moisture), and soil moisture conditions (including irrigation). These factors are described in Table 4.9.

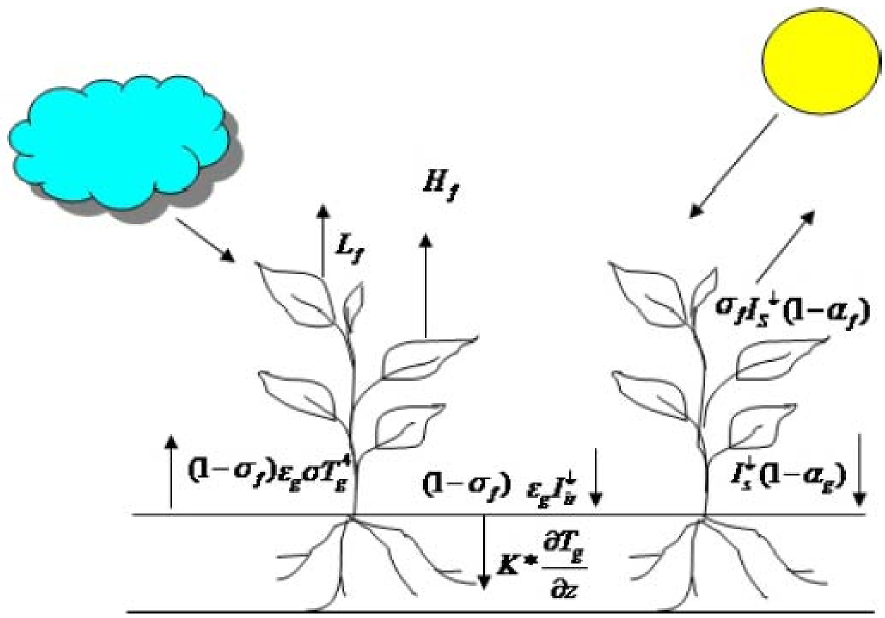


Figure 4.24 Energy balance for a green roof (Sailor, 2008)

Table 4.9 Green roof data for simulation models (Source: www.designbuilder.co.uk)

Green roof data	Description
Height of plants	The average height of plants in the green roof.
Leaf area index (LAI)	This is the projected leaf area per unit area of soil surface. It is a dimensionless number between 0.001 and 5.0.
Leaf reflectivity	The fraction of incident solar radiation that is reflected by the individual leaf surfaces. Solar radiation includes the visible spectrum as well as infrared and ultraviolet wavelengths. Values for this field must be between 0.1 and 0.4.
Leaf emissivity	This field is the ratio of thermal radiation emitted from leaf surfaces to that emitted by an ideal black body at the same temperature. This parameter is used when calculating the long wavelength radiant exchange at the leaf surfaces. Values for this field must be between 0.8 and 1.0 (with 1.0 representing “black body” conditions).
Minimum stomatal resistance	This field represents the resistance of the plants to moisture transport. It has units of s/m. Plants with low values of stomatal resistance will result in higher evapotranspiration rates than plants with high resistance. Values for this field must be in the range of 50.0 to 300.0.
Max volumetric moisture content of the soil layer (saturation)	Maximum volumetric moisture content of the soil depends on the properties of the soil and in particular the porosity.
Min (residual) volumetric moisture content of the soil layer	The minimum possible volumetric moisture content of the soil layer.
Initial volumetric moisture content of the soil layer	The volumetric moisture content of the soil layer at the start of the simulation. The moisture content will be updated during the course of the simulation based on surface evaporation, irrigation and precipitation.

5. Discussions

Roof greening is one of the environmental initiatives for providing a healthy and sustainable living environment in our society. It would enhance environmental benefits by improving thermal insulation, reducing glare and heat radiation so as to counteract UHI effects, as well as enhancing biodiversity, visual and aesthetic values (it could offer a pleasant view to the tenants from the tall buildings surrounding it too).

In general, the thermal effects of green roofs can be divided into two aspects:

(a) Direct effect to the building (internal)
(b) Indirect effect to the surrounding environment (external)

Direct effect of green roofs concerns the surrounding microclimate, and the immediate benefits to the building that contains this vegetation. These immediate benefits include altering the energy balance and cooling requirements of the building by improving the thermal insulation of the building with the use of the greenery (Wong, *et al.*, 2002). When plants or vegetation are planted on a larger basis, the general macroclimate of the area is modified. These changes affecting the area are referred to as indirect effects, which are associated with the space of the locality, rather than the immediate direct impacts.

5.1 Direct Effects of Green Roofs

From a thermal point of view, green roofs as well as living walls can prove beneficial for indoor thermal conditions (Alexandri and Jones, 2008). In addition to the fact that they add a further insulation layer to the building's fabric, they can decrease cooling load demands inside the building quite significantly due to the microclimatic modifications as described in Section 2.2. In addition to the energy savings themselves, this could lead to successful applications of further passive cooling techniques, especially ones employing ventilation, which are not easy to implement in the extremely hot urban conditions.

Wong, *et al.* (2002 & 2003b) analysed the effect of different types of green roofs on the energy consumption of a five storey commercial building in Singapore. They compared different types of vegetation layers (e.g., shrubs, trees and turfing) and various soil thickness. They reported total energy savings of 15% in relation to the energy consumption of the building with a common flat roof when a green roof composed by shrubs and 300 mm of clay soil with 40% moisture content was installed in a building with a roof to wall surface ratio of 0.2.

For tropical climate, the impact of different types of vegetation may vary as well; those with relatively extensive greenery coverage usually led to better thermal performance (Wong, Tan and Chen, 2007). Shadowing plants with larger horizontal foliage Leaf Area Index (LAI) reduces heat flux on the roof (Del Barrio, 1998), but designers should note when choosing species, that plants that offer better shading from heat gain may offer little insulating ability for retaining warmth if desired. The general guidelines for green roof selection are described below.

- Select plants with a large foliage development and/or with a mainly horizontal leaf distribution, in order to warrant a low solar radiation transmission (shadowing by the canopy layer)
- Select light soil that reduces the thermal conductivity as well as weight. A large field capacity, which is both beneficial for insulation purposes (soil thermal diffusivity reduces when soil moisture content increases) and for plants' development, is also desirable.

5.2 Indirect Effects of Green Roofs

Computer simulations conducted in Canada and Germany indicated that if 7% of urban rooftops are green, a 2 °C reduction in summer temperature can be achieved. Connelly and Liu (2005) showed that if green roofs made up 1% of total land area of Toronto or 6% of total roof area with green roof area of 6.5 million m^2, the reduction in the UHI would be around 1-2 ºC.

The placement of photovoltaic panels on green roofs has been found to have a double benefit in that the panels shade the roof from excessive sun exposure and high evaporation, thus reducing drought stress of plants and allowing for a wider range of planting choices from full sun to half shade (Köhler, 2006) The cooling effect from evapotranspiration of green roof planting enables a 6% higher efficiency of photovoltaic panels and enhances their overall performance.

People have also proposed planting trees, green roofs or living walls around buildings to reduce the thermal load of buildings and urban heat islands by exploiting the biological and physical functions of plants. Humid climates can benefit from green surfaces, especially when both walls and roofs are covered with vegetation, reaching up to 8.4 °C maximum temperature decrease for humid Hong Kong for instance (Alexandri and Jones, 2008).

If applied to only one unit block, green roofs and green walls can create a small area of mitigated temperatures to the urban heat island effect. If applied to the whole city scale, they could mitigate raised urban temperatures, and, especially for hot climates, bring temperatures down to more ‘‘human-friendly’’ levels and achieve energy saving for cooling buildings from 32% to 100% (Alexandri and Jones, 2007).

The cumulative effect of green roofs to the urban environment cannot be ignored. It should be noted that greening the city is not limited to rooftops; balconies, roadsides and traffic islands should also be landscaped into aesthetically pleasing gardens.

5.3 Key Design Factors

For the analysis of the green roofs cooling potential in buildings, Del Barrio (1998) pinpointed the important parameters including leaf area index (LAI), foliage geometrical characteristics, soil apparent density, soil thickness and soil moisture content. Vegetation would protect the roof from direct solar radiation and could cool it through enhanced evaporation. Usually, leaf area and foliage height thickness (vertical thickness of canopy) are the important factors governing the thermal reduction effect of plant layers on rooftops (Fang, 2008). Table 5.1 gives a summary of the key design factors.

Table 5.1 Key design factors of green roofs

Factor	Description
Density of vegetation	It is a vertical measurement of vegetation density, which depends on leaf area index (LAI) and type of plants.
Coverage ratio (CR)	Vegetation coverage on the bare roof is a horizontal measurement of vegetation density, which affects the effectiveness of thermal protection.
Moisture content of soil	A major factor for the effectiveness of evapotranspiration in vegetation.
Depth of soil layer	Affects the heat transfer by conduction and weight.
Total leaf thickness (TLT)	The thickness of leaves has a complementary relationship with coverage ratio.
Wind speed	It affects the rate of evaporation in the vegetation.
Colour of vegetation	Affects the amount of solar heat absorbed.

The extent of greening will be determined by the use and design of the roof, which usually include provision of planters, soft and hard landscaping, paving, decking and related waterproofing, irrigation and drainage system works.

When designing a green roof, it is important for the roof designer to get in early on the general building design process. The green roof designer needs to know the dead load capacity of the roof above the roof deck, i.e. the weight the roof can support less the weight of the roof deck, the roof structure and any items hanging from the roof.

Greening accounts for 10% to 80% of a building's total roof area, depending on the building services and communication facilities located on the roof. Similarly, the unit cost of roof greening, normally ranging from HK$700 to HK$2000 per m^2 (excluding the cost of structural works), is determined by the design, material specifications and site conditions, etc. (Urbis Limited, 2007).

5.4 Implications for Hong Kong

Under the greening policy, greening and landscaping have already been widely incorporated in the planning of new towns and new development areas in Hong Kong where landscape master plans are usually prepared at the early planning stage. The difficult part is in the urban areas where competition of land uses is keen and land cost is high thus limiting the scope for greening, except where there is opportunity for comprehensive redevelopment.

5.4.1 Major Constraints

Greening activities face a difficult situation because of disordered urbanization and the escalation in land prices. With increasing population and limited land, the Government had to adopt a high-density and high-rise residential strategy. Space constraints have reduced the applicability of green surfaces in various areas surrounding the building envelope. Consequently, green roofs become the only promising choice for densely populated urban cities like Hong Kong.

But like any innovation, lingering doubts about green roofs still persist, worries ranging from costs, leakage to mosquito prevent the widespread adoption of green roofs. Financial incentives, public awareness and building codes can help hasten the adoption of green roofs and other measures, it is important to help property owners and developers to look beyond the immediate financial burden to realise the long-term benefits and the pressing need to change the urban environment.

5.4.2 Opportunities

In Japan, the city of Tokyo has initiated a new ordinance in recent years to install green roofs on new buildings with floor space more than 1000 m^2. A comprehensive approach to mitigate the UHI is adopted and the major strategies are shown on Figure 5.1. Roof greening is an important measure and has grown by more than 18 times in the past decade.

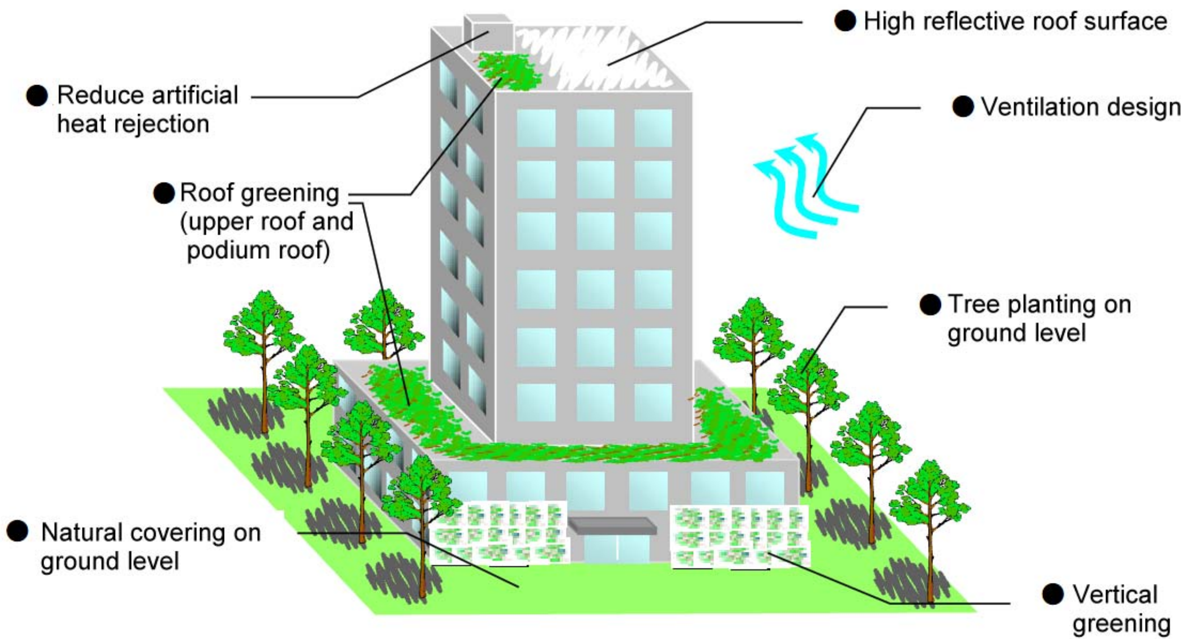


Figure 5.1 Strategies to mitigate urban heat island
(Source: Tokyo Metropolitan Government, www.metro.tokyo.jp)

For Hong Kong, with the dominance of hard-paved surfaces including roofs, vertical faces and street level, there is an urgent need to review administrative/legislative measures to promote roof and multi-level greening. In the urban area, the greening can enhance the quality of our living environment and provide opportunities for other community functions. The opportunities in Hong Kong for promoting multi-level greening include:

- Roof garden
- Sky garden
- Podium garden
- Edge greenery
- Living wall

Control of the solar radiation is a critical point for the climate of Hong Kong. If large amount of solar energy are absorbed for the growth of plants through their biological functions, such as for green roof and urban farming, then the thermal energy balance of the city can be better managed.

6. Conclusions

Green roofs could contribute positively to the improvement of the thermal performance of a building through direct and indirect effects. They also have a potential to decrease energy demand by reducing the heat flux from a building roof.

(a) Literature Study

The heat flux transfer of green roofs is governed by four mechanisms: shading, thermal insulation, evapotranspiration and thermal mass. The thermal and energy performance of green roofs has been studied world wide using three different approaches: field experimentation, numerical studies, and a combination of laboratory or field experiments with numerical models. In general, of the total solar radiation absorbed by the green roof, about 27% is reflected, 60% is absorbed by the plants and the soil through evaporation, and 13% is transmitted into the soil.

The literature review studies indicated that green roofs can substantially reduce the roof surface temperatures and heat flux from a building roof. However, the studies also showed significant differences in the magnitude of the heat flux and energy reduction. For example, from a study of a two-storey building in USA, they found that as compared with a conventional flat membrane roof, the green roof can reduce the heat flux by 18% to 50%. Also, a simulation study of a green roof on a 5-storey office building in Singapore showed annual energy consumption savings of 1% to 15% depending on characteristics of the green roof.

Green roof systems could contribute positively to the mitigation of urban heat island and enhancement of building thermal and environmental performance. It is found from other research that green roofs have a greater potential for reducing heat gain rather than preventing heat loss in the fall and winter.

(b) Field Studies and Measurements

Investigation was carried out on three green roof sites proposed by the EMSD with retrofitting green roof projects in existing government buildings and one pilot green roof project in a school building proposed by the HKU. These green roof sites represented different types of designs and situations for the application of extensive and semi-intensive green roofs. To assess the thermal and energy performance, suitable instrumentation and methodology have been determined for carrying the measurements in July to September 2009.

The measurements results showed that the green roofs can significantly moderate the daily temperature fluctuations experienced by the roof membrane. Maximum temperature attenuation (i.e. daily temperature fluctuation of bare roof versus that of green roof) of 9.8 °C (at 4/F of APB Centre) to 18.4 °C (at NTK Building taller plants) was recorded. However, during the night time, the cooling effect of the green roof diminished.

Moreover, the drying of green roof plants and soil will affect the thermal effect because low water content in the soil, poor vegetation cover and plant health do not provide adequate evaporation to consume heat. When the soil bases are ultra-thin and very dry, the so-called “inversion phenomenon” may occur, promoting more heat into the building. Thus, the moisture and maintenance of green roof are very important to ensure healthy plants and performance.

In the correct climate, the adiabatic effect of a green roof is significant, and can help reduce the need for air conditioning. However, accurate estimates of energy savings must be made based on the water content of the soil at any given time.

(c) Numerical and Simulation Models

The overall thermal transmittance, U-value, is an important concept for thermal performance in building design. It represents how well an element conducts heat from one side to the other, which makes it the reciprocal of its thermal resistance.

Based on a steady-state Fourier theory in one dimension, the U-values of the green roof sites were estimated. The contribution of the green roofs varied from 16% (10/F of APB Centre) to 42% (Yuen Long Government Primary School), depending on the soil thickness and roof construction.

For the heat transfer of roof elements, if the roof is very well insulated or if there is a ventilated space between the roof surface and the building interior, then adding a green roof will provide no further significant increase in thermal resistance. The choice of materials in the planted part of the roof does not greatly influence the thermal behaviour of a thermally insulated roof. But when the roof is not thermally insulated, the influence will be more significant.

The roof-envelope ratio impact on green roof energy performance has also been considered. To study how the roof-envelope ratio affects the relative importance of roof thermal load, a building energy simulation model was set up and computations were performed using the Energy-10 simulation software.

It is found that for the topmost floor of the building, the roof thermal load constitutes 15.3% and 24.3% of building electrical energy consumption and building electrical peak demand, respectively. For high-rise buildings, these percentage figures will decrease accordingly. For 10-storey, 20-storey and 30-storey buildings, the percentage of roof load to whole building total electrical energy are only 1.8%, 0.9% and 0.6%, respectively (see Figure 4.19). Therefore, even if a green roof can reduce the roof thermal load significantly, the overall impact on the whole building energy consumption (the direct effect) is not large for high-rise buildings. However, the indirect effect to urban temperature would be essential when a large scale greening is adopted.

(d) Assessment of Thermal and Energy Performance

Based on the assessment of U-value and the linear regression equation developed from the building energy simulation, a rough estimation of the effects of green roofs for the four green roof sites is done. The results indicate that when the percentage of green roof area is taken into account, the reduction of the U-value of the whole roof slab is from 1.4% (10/F of APB Centre) to 31.9% (Yuen Long Government Primary School). The corresponding percentage saving of annual total building electrical energy (for top floor only) would range from 0.1% (10/F of APB Centre) to 4.6% (Yuen Long Government Primary School). When more floors are considered, these figures will be reduced further.

The thermal and energy performance of adding a green roof to a bare roof can be studied generally by assessing the thermal resistance of green roofs and the effects on different types of roof structures. The percentage change of the roof U-value (indicates the thermal performance) and the percentage change of annual total building electrical energy use (indicates the energy performance) were calculated and the key analysis results are shown in Figures 4.22 and 4.23. Using these two graphs, the effects of adding green roof can be estimated, by checking the U-value of bare roof and the R-value of green roof.

The U-value calculations have ignored the thermal resistance of the canopy plant layer and the indirect effect of heat transfer from the green roof to the surrounding environment. More detailed simulation models will be needed if these factors are to be considered carefully.

(e) Recommendations

Apart from enhancing the city landscape and environment, mitigating the urban heat island effect and improving air quality, green roof can improve the microlimate and increase the life span of waterproof and insulation facilities on the roof. Consequently, roof greening with a sufficient large scale is conducive to energy conservation and life cycle cost saving for the urban city.

It is found from other research that the placement of photovoltaic panels on green roofs has a double benefit in that the panels shade the roof from excessive sun exposure and high evaporation, thus reducing drought stress of plants and allowing for a wider range of planting choices from full sun to half shade. At the same time, the cooling effect from evapotranspiration of green roof planting enables a 6% higher efficiency of photovoltaic panels and enhances their overall performance.

Green roofs can help reduce three of the four top problems facing the society in the next 50 years: energy, water, and environment. In this way, the green roof technology has a potential to improve quality of population health and welfare in the urban areas with dramatically reduced vegetation. Hopefully this will lead to a holistic green building – better ventilation, shade, micro-climate, less energy reliance for the city.

It is recommended that further studies be carried out to investigate both direct and indirect effects of green roofs, in particular urban heat island effect, in Hong Kong and to review administrative/legislative measures to promote roof and multi-level greening in the urban area.

References

Alcazar, S. S. and Bass, B., 2005. Energy performance of green roofs in a multi storey residential building in Madrid, In *Proceedings of Greening Rooftops for Sustainable Communities*, May 5, 2005, Washington, D.C., pp. 569-582.

Alexandri, E. and Jones, P., 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates, *Building and Environment*, 43 (2008): 480-493.

Alexandri, E. and Jones, P., 2007. Developing a one-dimensional heat and mass transfer algorithm for describing the effect of green roofs on the built environment: comparison with experimental results, *Building and Environment*, 42 (2007): 2835-2849.

Al-Sanea, S., 2002. Thermal performance of building roof elements, *Building and Environment*, 37 (7): 665–675.

ASTM, 2006. *ASTM E2400-06, Standard Guide for Selection, Installation, and Maintenance of Plants for Green Roof Systems*, American Society for Testing and Materials, West Conshohocken, PA.

Banting, D., *et al.*, 2005. *Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto*, Ryerson University, Toronto, Ontario.

Bass, B. and Baskaran, B., 2003. *Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas*, NRCC-46737, Institute for Research in Construction, National Research Council Canada, Ontario, Canada.

BD, 2009. *Consultancy Study on Building Design that Supports Sustainable Urban Living Space in HK, Final Report*, Consultancy Agreement No. BA/01/2006, Buildings Department (BD), Hong Kong.

Connelly, M. And Liu, K., 2005. Green roof research in British Columbia – An Overview, In *Proceedings of the Greening Rooftops for Sustainable Communities*, May 4-6, 2005, Washington, DC, 17 pages.

Davies, M. G., 2004. *Building Heat Transfer*, J. Wiley & Sons, Chichester, West Sussex and Hoboken, NJ.

Del Barrio, E. P., 1998. Analysis of the green roofs cooling potential in buildings, *Energy and Buildings*, 27 (1998): 179–193.

Doshi, H., *et al.*, 2005. *Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto*, Ryerson University, Ontario, Canada.

Dunnett, N. and Kingsbury, N., 2008. *Planting Green Roofs and Living Walls*, Revised and Updated Edition, Timber Press, Oregon.

Eumorfopoulou, E. and Aravantinos, D., 1998. The contribution of a planted roof to the thermal protection of buildings in Greece, *Energy and Buildings*, 27 (1998): 29–36.

Fang, Chih-Fang, 2008. Evaluating the thermal reduction effect of plant layers on rooftops, *Energy and Buildings*, 40 (2008): 1048-1052.

FLL, 2004. *Guidelines for the Planning, Execution and Upkeep of Green-roof Sites: Roof-greening Guidelines*, January 2002 edition, 1st ed. August 2004 (English version), Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL), Bonn.

Forbes, R., 2006. *The Green Roof Pocket Guide*, The Green Roof Forum, Sheffield, UK (available at www.livingroofs.co.uk)

Hui, S. C. M. and Chan, H. M., 2008. Development of modular green roofs for high-density urban cities, paper presented at the *World Green Roof Congress 2008*, 17-18 September 2008, London, 12 pages.

Hui, S. C. M. and Chu, C. H. T., 2009. Green roofs for stormwater mitigation in Hong Kong, In *Proceedings of Joint Symposium 2009: Design for Sustainable Performance*, 25 November 2009, Kowloon Shangri-La Hotel, Hong Kong, 15 pages.

Hui, S. C. M., 2006. Benefits and potential applications of green roof systems in Hong Kong, In *Proceedings of the 2nd Megacities International Conference 2006*, 1-2 December 2006, Guangzhou, China, pp. 351-360.

Hui, S. C. M., 2004. Sustainable design and operation of construction site offices, In *Proc. of the Shenyang-Hong Kong Joint Symposium 2004*, 29-30 July 2004, Shenyang, China, pp. A119-A128.

Jim, C. Y., 2007. Pioneering research green roof at the University of Hong Kong, *Green Roof News* (International Green Roof Association newsletter), Spring 2007, page 6.

Köhler, M., 2006. Long-term vegetation research on two extensive green roofs in Berlin, *Urban Habitats*, 4 (1): 3-26.

Köhler, M., *et al.*, 2002. Green roofs in temperate climates and in the hot-humid tropics - far beyond the aesthetics, *Environmental Management and Health*, 13 (4): 382-391.

Kumar, R. and Kaushik, S. C., 2005. Performance evaluation of green roof and shading for thermal protection of buildings, *Building and Environment*, 40 (11): 1505-1511.

Lazzarin, R. M., Castellotti, F. and Busato, F., 2005. Experimental measurements and numerical modelling of a green roof, *Energy and Buildings*, 37 (12): 1260-1267.

Liu, K., 2003. *Engineering Performance of Rooftop Gardens through Field Evaluation*, NRCC-46294, National Research Council, Institute for Research in Construction, Ottawa, Ontario, Canada.

Liu, K. K. Y., 2002. Energy efficiency and environmental benefits of rooftop gardens, *Construction Canada*, 44 (2), March 2002, p. 17, 20-23.

Loh, S., 2009. Green roofs – understanding their benefits for Australia, *BDP Environment Design Guide*, TEC 27, 12 pages, www.environmentdesignguide.net.au.

Luk, H. K., *et al.*, 2006. Quantitative analysis of green rooftop (GRT) technology effects on air quality and energy usage in Hong Kong, presentation at *the HKSTAM 2005/2006 Annual Meeting*, 11 March 2006, Hong Kong Society of Theoretical and Applied Mechanics (HKSTAM), Hong Kong.

Martens, R., Bass, B. and Alcazar, S. S., 2008. Roof-envelope ratio impact on green roof energy performance, *Urban Ecosystems*, 11 (2008): 399-408.

Niachou, A., *et al.*, 2001. Analysis of the green roof thermal properties and investigation of its energy performance, *Energy and Buildings*, 33 (2001); 719–729.

Nichol, J. E., *et al.*, 2009. Urban heat island diagnosis using ASTER satellite images and 'in situ' air temperature, *Atmospheric Research*, 94 (2): 276-284.

NRCA, 2007. *The NRCA Green Roof Systems Manual*, National Roofing Contractors Association (NRCA), Rosemont, IL.

O'Keeffe, G., *et al.*, 2008. Design of an instrumented model green roof experiment, *Geotechnical Special Publication*, Issue 178 (2008): 1105-1112.

Ondimu, S. N. and Murase, H., 2006. Thermal properties of living roof green material by inverse modelling, *Applied Engineering in Agriculture*, 22 (3): 435–441.

Onmura, S., Matsumoto, M. and Hokoi, S., 2001. Study on evaporative cooling effect of roof lawn garden, *Energy and Buildings*, 33 (2001): 653-666.

Peck, S. W., Callaghan, C., Kuhn, M. E. and Bass, B., 1999. *Greenbacks from Green Roofs: Forging a New Industry in Canada, Status Report on Benefits, Barriers and Opportunities for Green Roof and Vertical Garden Technology Diffusion*, Canadian Mortgage and Housing Corporation (CMHC), Ottawa, Ontario, Canada.

Sailor, D. J., 2008. A green roof model for building energy simulation programs, *Energy and Buildings*, 40 (2008): 1466-1478.

Sailor, D. J., Hutchinson, D. and Bokovoy, L., 2008. Thermal property measurements for ecoroof soils common in the western U.S., *Energy and Buildings*, 40 (2008): 1246-1251.

Santamouris, M., *et al.*, 2007. Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece, *Energy*, 32 (9): 1781-1788.

Sonne, J. and Parker, D., 2008. Energy performance aspects of a Florida green roof: Part 2, In *Proceedings of the Sixteenth Symposium on Improving Building Systems in Hot and Humid Climates*, Dallas, Texas, December 15-17, 2008, FSEC-PF-442-08, Florida Solar Energy Center, University of Central Florida, Cocoa, Florida, 15 pp.

Sonne, J., 2006a. Energy performance aspects of a Florida green roof, In *Proceedings of the Symposium on Improving Building Systems in Hot and Humid Climates*, Orlando, Florida, July 24-26, 2006, ESL-HH-06-07-17, 7 pp.

Sonne, J., 2006b. Evaluating green roof energy performance, *ASHRAE Journal*, 48 (2): 59–61.

Spala, A., *et al.*, 2008. On the green roof system. Selection, state of the art and energy potential investigation of a system installed in an office building in Athens, Greece, *Renewable Energy*, 33 (2008); 173-177.

Spolek, G., 2008. Performance monitoring of three ecoroofs in Portland, Oregon, *Urban Ecosystem*, 11 (2008): 349-359.

Takakura, T., Kitade, S. and Goto, E., 2000. Cooling effect of greenery cover over a building, *Energy and Buildings*, 31 (2000): 1–6.

The Standard staff reporter, 2006. Green roofs lower room temperature, *The Standard*, Wednesday, September 27, 2006, p. E02.

Theodosiou, T. G., 2003. Summer period analysis of the performance of a planted roof as a passive cooling technique, *Energy and Buildings*, 35 (9): 909-917.

Urbis Limited, 2007. *Study on Green Roof Application in Hong Kong, Final Report*, Architectural Services Department, Hong Kong. (Available at www.archsd.gov.hk)

Velazquez, L., 2003. Modular green roof technology: an overview of two systems, In *Proceedings of the First Annual Greening Rooftops for Sustainable Communities Conference, Awards & Trade Show 2003*, Chicago, Illinois.

Weiler, S. and Scholz-Barth, K., 2006. *Green Roof Systems: A Guide to the Planning, Design and Construction of Building Over Structure*, John Wiley, Hoboken, N.J. and Chichester.

Wong, N. H. and Chen, Y., 2009. *Tropical Urban Heat Islands: Climate, Buildings and Greenery*, Taylor & Francis, London and New York.

Wong, N. H., Tan, P. Y. and Chen, Y., 2007. Study of thermal performance of extensive rooftop greenery systems in the tropical climate, *Building and Environment*, 42 (1): 25-54.

Wong, N. H., *et al.*, 2003a. Investigation of thermal benefits of rooftop garden in the tropical environment, *Building and Environment*, 38 (2003): 261–270.

Wong, N. H., *et al.*, 2003b. The effects of rooftop garden on energy consumption of a commercial building in Singapore, *Energy and Buildings*, 35 (2003): 353-364.

Wong, N. H., *et al.*, 2002. The thermal effects of plants on buildings, *Architectural Science Review*, 45 (4): 337-348.

Yokoyama, H., *et al.*, 2007. Study of mitigating urban heat islands by rooftop greenery system with container tank of rain water, *Annual Journal of Tokyo Metropolitan Research Institute for Environmental Protection*, 2007, p. 12-16. (in Japanese)

Yokoyama, H., Yamaguchi, T. and Ishii, K., 2004. Study of mitigating urban heat islands by light and thin rooftop greening, *Annual Journal of Tokyo Metropolitan Research Institute for Environmental Protection*, 2004, p. 3-10. (in Japanese)

Zhang, W., *et al.*, 2006. Research on the effect of a planting roof on the thermal load of a business building, In *Proceedings of the ICEBO - International Conference for Enhanced Building Operations*, Shenzhen, China, November 6-8, 2006, ESL-IC-06-11-55, 5 pp.

Zinco, 2000. *Green Roofs: Recommended Standards for Designing and Installation on Roofs: Planning Guide*, 6th ed., Zinco GmbH, Unterensingen.