Guidelines for the design and application of green roof systems

CIBSE

Guidelines for the design and application of green roof systems

Prepared by:
Dr Sam CM Hui
Department of Mechanical Engineering
The University of Hong Kong

CIBSE

For any enquiries about the guidelines, please contact:

Dr Sam CM 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
http://web.hku.hk/~cmhui

Registered charity number 278104

ISBN 978-1-906846-40-4

Layout and typesetting by Bonnie Craig

Printed in Great Britain by The Lavenham Press, Lavenham, Suffolk CO19 9RN

Cover illustration: Cyrus Dowlatshahi

Note from the publisher

This publication is primarily intended to provide guidance to those responsible for the design, installation, commissioning, operation and maintenance of building services. It is not intended to be exhaustive or definitive and it will be necessary for users of the guidance given to exercise their own professional judgement when deciding whether to abide by or depart from it.

Any commercial products depicted or described within this publication are included for the purposes of illustration only and their inclusion does not constitute endorsement or recommendation by the Institution.

Foreword

Many cities in the world are facing problems of urban heat islands (UHIs) and a lack of green space. Among growing concerns about environmental issues and the need to promote sustainable urban environments, green roofs have recently attracted much attention. However, the market for green roofs is still developing, and more information and understanding on their technical design, effectiveness and actual benefits are needed.

Green roofs are not a new phenomenon; they have been standard construction practice in many countries for thousands of years. The ancient Babylonians incorporated elaborate vegetated roofs in the Hanging Gardens' terraced structures, built around 500 BC and considered one of the Seven Wonders of the Ancient World. Many European and developed countries and cities provide incentives or requirements for green roof installation.

The environmental, social and visual contributions that green roofs can make towards creating sustainable living environment in high-density cities are accepted worldwide. It is believed that green roofs and other 'greening methods' will become an important feature in the urban landscape and can perform a vital role in helping cities adapt to the effects of climate change. However, they can only provide these environmental benefits if designed and installed in way that ensures minimum performance criteria are met. Although green roof technology is relatively straightforward, it is possible for people who are unfamiliar with the technology to make mistakes or miss opportunities to maximise the benefits.

These guidelines highlight the important considerations for green roof planning, design, installation and maintenance, and provide guidance as to how they can be accommodated in the final green roof scheme. They aim to promote awareness of green roofs, facilitate effective planning, design and implementation of sustainable green roof projects and stimulate an increase in the uptake of green roofs on new developments and existing buildings.

These guidelines provide key information and general guidance on green roof design, specification, installation and maintenance. However, there will be special cases where additional considerations will need to be made. These guidelines do not cover certain technical areas of green roof technology, such as drainage flow rates, growing medium performance criteria or waterproofing. For this kind of technical information refer to the reference documents and relevant standards described in Appendices A3 and A4.

Green roofs offer an important way forward in urban greening, bringing natural wildlife back into the urban realm and providing much-needed ecosystem services to the built environment. Our cities and towns need to embrace green roofs to ensure that we adapt and mitigate our impact on the environment to achieve a liveable-quality and sustainable built environment.

Dr Sam CM Hui

Project Chair: David Hughes

Project Manager: Sanaz Nazemi Agha

Editor: Bonnie Craig

Acknowledgements

This work was sponsored by the Chartered Institution of Building Services Engineers (CIBSE) Hong Kong Branch.

The author would like to thank the following people and organisations for providing support and assistance.

- CIBSE Hong Kong Branch
- The University of Hong Kong (Department of Mechanical Engineering)
- Ir Professor KK Lam, CIBSE Hong Kong Branch
- Mr Wilson WP Lam, Architectural Services Department
- Ir CK Mok, CIBSE Hong Kong Branch
- Mr Tsang Wai Man Wyman, The University of Hong Kong
- Mr WW Ho, Zinco Singapore Pty Ltd
- Dr Karen KY Liu, Xero Flor International
- Mr John CW Yau, Hong Kong Greenlink Küster Co Ltd

Sincere thanks are expressed to the following organisations for providing information on green roof systems.

- Architectural Services Department, Hong Kong SAR Government
- Centre for Urban Greenery and Ecology, Singapore
- Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (Research Society for Landscape Development and Landscape Design), Germany
- Green Roofs for Healthy Cities, Canada
- Green Roof Organisation, UK
- Housing and Development Board, Singapore
- International Green Roofs Association
- St Bonaventure Catholic Primary School, Wong Tai Sin, Kowloon, Hong Kong

The Institution gratefully acknowledges the following for reviewing the draft prior to publication:

- Dusty Gedge
- Cath Hassell
- David Hughes

Contents

1 Introduction

Green roof systems are living vegetation installed on roofs and can provide many environmental and social benefits for achieving low-carbon, high-performance building (Hui, 2010). They can make cities more liveable by providing green spaces, mitigating urban heat islands (UHI), reducing air quality problems, enhancing stormwater management and increasing biodiversity (Cantor, 2008; Banting, *et al*., 2005; Dunnett and Kingsbury, 2008; Hassell and Coombes, 2007; Hui, 2006). Figure 1.1 shows an application of a large green roof system in Germany. It is installed on the roof of an industrial logistics building.

Figure 1.1 A large green roof system in Germany: Aldi Logistics Centre, St. Augustin, Germany (35 000 m^2)
Credit: © xeroflor

Many cities in the world are facing problems of UHIs and lack green space. Developed cities have extremely high population densities so the urban environment is threatened by an intense UHI effect, which urban greening can help to resolve (BD, 2009; Hui, 2009). Green roofs can help mitigate the adverse effects of UHI and bring nature back to the urban area (Hui and Chan, 2008; Kumar and Kaushik, 2005; Liu, 2003; NRCA, 2009). They help to lower urban temperatures, improve aesthetics and urban psychology, and reduce pollutant concentrations and noise (Wong and Chen, 2009; Wong, Tan and Chen, 2007). Figure 1.2 shows two examples of green roof systems applied in urban cities in Japan (Fukuoka) and Canada (Vancouver). They are located in downtown areas of the cities and surrounded by other buildings. There is currently a growing global demand for green roofs and urban greenery.

1.1 Purpose

These guidelines provide practical information on green roof systems for education and effective application. They establish recommendations and requirements on green roof planning, design, construction, maintenance and project management, which apply in general terms to the urban environment. They are for professionals and people who are considering taking advantage of the economic, social and environmental benefits that green roofs offer.

Figure 1.2 Green roof systems in Japan and Canada:
Left: ACROS Fukuoka Prefectural International Hall, Fukuoka, Japan
Credit: Emilio Ambasz, Architect
Right: Library Square Building in downtown Vancouver, BC, Canada
Credit: Photo courtesy of American Hydrotech, Inc

After reading the guildelines you should be able to understand the following:

- the basic types and structure of green roofs
- the multitude of potential green roof benefits
- the important knowledge and best practice for green roof projects
- the key technical issues in planning, design, construction, maintenance and project management of green roof systems.

The guidelines are divided into three parts. Useful references from overseas have been studied (Dvorak, 2011; FLL, 2008; Loesken, 2009). Hong Kong data and information is also used, where appropriate.

- Part 1
  - Chapter 1: Introduction
  - Chapter 2: Scope
  - Chapter 3: Definitions
- Part 2
  - Chapter 4: Planning requirements
  - Chapter 5: Design considerations
  - Chapter 6: Construction methods
  - Chapter 7: Maintenance issues
  - Chapter 8: Project management
- Part 3
  - References
  - Appendices

By clarifying the myths surrounding green roof installations and developing reliable guidance, these guidelines aim to promote industry confidence and to prevent low-quality products and construction from entering and dominating the market. Other resources and further information about green roof systems can be found in the References and in Appendix A1.

1.2 Benefits of green roofs

Green roofs can address many of the challenges facing urban cities. It is well proven that green roofs are an investment that provides a significant number of social, environmental and economic benefits (Banting *et al.*, 2005). They can:

- reduce energy demand on air conditioning
- reduce rainwater runoff
- expand the lifetime of roofing membranes
- mitigate the UHI effect in cities
- improve air quality
- enhance biodiversity
- add aesthetic appeal
- increase property values.

1.2.1 Urban management

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

Apart from enhancing the city landscape and environment, mitigating the UHI effect and improving air quality, green roofs can improve the microclimate and increase the lifespan of waterproof and insulation facilities on the roof. Consequently, roof greening on a large enough scale is conducive to energy conservation and lifecycle cost saving for the urban city.

Green roofs have an important role to play in the society's commitment to a more sustainable future. They provide a visual display and expression of the city's intent to develop environmentally sustainable, climate-adapted urban management. The marketing benefits could encourage both private and public sectors to consider green roof projects.

1.2.2 Public and private benefits

Green roofs provide a wide range of benefits from amenity to ecological and technical advantages to financial aspects (Hui, 2006). Table 1.1 gives a summary of the public and private benefits of green roof systems. Cities can benefit from green roofs both in visual, aesthetic and local human climatic amelioration, but it is not easy to quantify these factors for economic comparison.

Table 1.1 Public and private benefits of green roof systems

Public benefits	Private benefits
▪ Aesthetic value ▪ Mitigate UHI ▪ Stormwater retention ▪ Create wildlife habitat ▪ Functional open space ▪ Agricultural space ▪ Filter dust and pollutants ▪ Filter rainwater	▪ Increase roof lifespan ▪ Reduce cooling loads ▪ Contribute to green building rating credit points ▪ Better use of space ▪ Reduce noise levels ▪ Reduce risk of glare for surrounding buildings

The social benefits of promoting green roofs should not be overlooked. For example, public housing can provide senior citizens and families with safe, accessible green space on top of the buildings, as well as improving their quality of life. Schools can integrate curricula and provide added green space for students' experimental learning (outdoor rooftop classrooms). Hospitals and other health-care facilities can provide opportunities on green roofs for horticultural therapy—a proven method of speeding recovery rates and reduction of drug use. Commercial buildings can create green space and roof gardens for relaxing and promoting horticulture or community farming. Industrial buildings can incorporate specialised green roofs for cooling, to provide amenity space for employees, or simply to improve the aesthetic surroundings for buildings that overlook the roof.

If the site conditions permit, green roofs can also be designed to generate urban agricultural opportunities for the production of high-quality organic foods, and medicinal and ornamental plants (Hui, 2011). This has the advantages of reducing associated transportation and refrigeration costs, reducing the time and distance from field to table, ensuring ripeness at harvest, and providing new employment opportunities for city dwellers (see also section 5.7).

1.3 Major barriers

Greening activities in urban cities often face a difficult situation because of disordered urbanisation and the escalation in land prices. With increasing population and limited land, government policy may directly or indirectly result in development proposals tending to adopt a high-density or high-rise strategy. Thus, space constraints have reduced the applicability of green surfaces in various areas surrounding the building envelope.

Like any innovation, lingering doubts about green roofs still persist; worries range from cost to leakage to mosquito infestation (in warm climate regions). 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.

1.3.1 Constraints and barriers

Urbis Limited (2007) has indicated the following key constraints affecting green roof development in Hong Kong:

- lack of knowledge and awareness
- lack of incentive/statutory mandate
- economic constraints
- lack of available roof area
- technical issues and risks associated with uncertainty.

Shepard (2010) also identified similar challenges in the USA.

Oberlander, Whitelaw and Matsuzaki (2002) in Canada studied the major barriers to green roofs and found the following barriers:

- economic and safety issues
- maintenance issues
- education
- permits.

From the economic point of view, there is a disconnection between who bears the cost of a green roof and who benefits. A developer may erect a building intending to sell it as soon as constructed. To keep costs low and maximise profits, amenities like green roofs will not be included unless required or encouraged. Table 1.2 shows the green roof benefits for developers, owners and the community. In order to overcome the barriers, more people need to understand the significance of greening, and green roof policies need to be designed.

Table 1.2 Green roof benefits for developers, owners and community

Benefit	Developer	Owner	Community
Aesthetics and property values	✓✓	✓✓	✓
Mitigate UHIs			✓
Stormwater retention	✓	✓	✓✓
Create natural habitat			√
Provide functional open space	✓✓	✓✓	✓✓
Provide agricultural space	✓	✓	✓
Filter dust and pollutants		✓	✓
Filter rainwater			✓
Carbon sequestration			✓✓
Increase roof lifespan	✓✓	✓✓	
Reduce cooling loads		✓✓	
Green building rating credit points	✓✓	✓	
Reduce noise levels		✓	✓
Reduce risk of glare		✓	✓
Possible food production		✓	✓✓
Increase property value	✓✓	✓✓	
Improve efficiency of solar photovoltaic (PV) panels	✓✓	✓✓	

1.3.2 Hong Kong as an example

In these guidelines, Hong Kong is used as an example of an urban city that is trying to promote greening for overcoming environmental and sustainability issues. Hong Kong has a subtropical hot and humid climate and often faces typhoon and stormwater problems during the rainy season (Hui and Chu, 2009). Strong winds and heavy rainstorms can cause flooding and seriously damage society. The most important climatic factors affecting rooftop greening include the following issues.

- Typhoons: the strong wind might blow away the vegetation and soil so modules and plants must be well secured and protected.
- Heavy rainfalls: the green roofs should be able to hold and drain rainwater without creating pools of stagnant standing water.
- High temperatures: heat stress can affect plant growth and development by influencing photosynthesis, respiration, water relations and membrane stability.
- Strong sunlight: strong solar and UV radiation might cause photo-oxidative problems to the green roof materials and components (such as plastics and wood), limiting their useful life.

Although there have been many applications of green roof technology in the world, not all green roofs have remained green or performed equally (Dvorak, 2011). Potential pitfalls for green roofs include:

- poor drainage and inadequate growth-medium design
- exceeding structural designs
- plant failures
- difficulties with maintenance.

It is important to have guidelines and performance standards for green roof systems for areas such as Hong Kong; it is hoped that the information will be helpful to other cities and countries.

2 Scope

Green roof systems are also referred to as green roofs, living roofs, roof gardens, eco-roofs, landscaped roofs and vegetated roof covers. The green roof systems in theses guidelines are typified by a top layer of living plant material and soil (growing medium or engineered soil) supported on the roofing assembly below. Green roofs are constructed using components that:

- have the strength to bear the added weight
- seal the roof to stop water, water vapour and roots penetrating
- retain enough moisture for the plants to survive periods of low precipitation, yet are capable of draining excess moisture if required (i.e. water storage and drainage)
- provide soil-like substrate material to support the plants
- maintain a sustainable plant cover, appropriate for the climatic region
- offer a number of hydrologic, atmospheric, thermal and social benefits for the building, people and the environment
- protect the underlying components against UV and thermal degradation.

Depending on the types of systems to be used, the components in green roofs may generally be the same as those in rooftop gardens, differing only in depth and project-specific design application (see section 3.1 for the typical green roof structure). The appearance and vegetation of the green roofs will vary for different climatic and geographical regions. Figure 2.1 shows examples of modern green roof projects in Malaysia (a convention centre) and the Netherlands (a university building), which have tropical and temperate climate, respectively. Figure 2.2 shows another two examples for municipal buildings in tropical Singapore.

Figure 2.1 Examples of modern green roofs in Malaysia and the Netherlands
Left: Putrajava International Convention Centre, Malaysia
Right: IBN-DLO Wageningen, the Netherlands

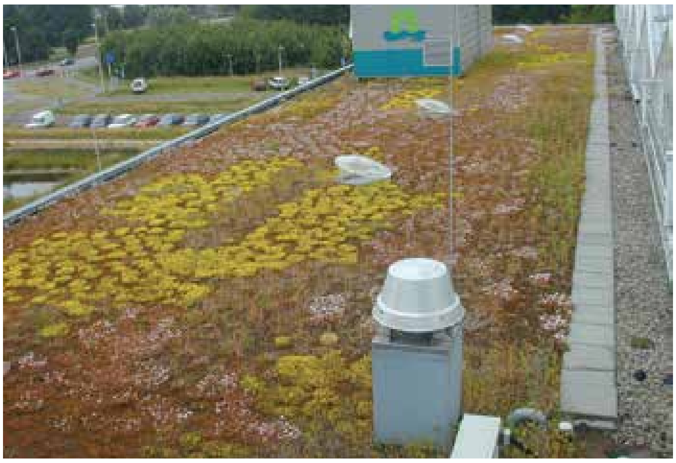


Figure 2.2 Examples of modern green roofs in Singapore
Left: Senja Cashew Community Club, Singapore
Credit: Verditecture Pte Ltd www.verditecture.com
Right: Marina Barrage, Singapore (14 000 m²)
Credit: PUB, Singapore's national water agency

2.1 Green roof types

Modern roof greening has two main approaches: intensive and extensive (Dunnett and Kingsbury, 2008; Weiler and Scholz-Barth, 2009; ZinCo, 2000). Extensive green roof systems typically have 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 have system profiles ranging 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 (although they require more maintenance). Figure 2.3 shows two examples of extensive and intensive green roofs in the UK and Germany, respectively.

Semi-intensive green roofs fall between extensive and intensive green roof systems. Table 2.1 shows the major types of green roofs and their characteristics. Depending on site-specific factors such as location, structural capacity of the building, budget, client needs, and material and plant availability, each individual green roof will be different—often a combination of intensive, semi-intensive and extensive systems. Appendix A2 provides further information about different types of green roof systems that are defined and applied in other countries in the world.

Figure 2.3 Examples of extensive and intensive green roofs
Left: Extensive green roof (Sedum House, South Yorkshire, UK)
Credit: Shutterstock
Right: Intensive green roof (Schlossle-Galerie, Pforzheim, Germany)
Credit: Optigreen

Table 2.1 Major types of green roofs and their characteristics (Hui, 2006)

Characteristics	Extensive	Semi-intensive	Intensive
Depth of material	150 mm or less	Above and below 150 mm	More than 150 mm
Accessibility	Often inaccessible	May be partially accessible	Usually accessible
Fully saturated weight	Low (70–170 kg/m^2)	Varies (170–290 kg/m^2)	High (290–970 kg/m^2)
Plant diversity	Low	Greater	Greatest
Plant communities	Moss-sedum-herbs and grasses	Grass-herbs and shrubs	Lawn or perennials, shrubs and trees
Use	Ecological protection layer	Designed green roof	Park-like garden
Cost	Low	Varies	Highest
Maintenance	Minimal	Varies	Highest

Because of their light weight, and lower capital and maintenance costs, extensive green roofs are growing in popularity in the world for temperate, tropical and other climates. Figure 2.4 shows two examples of extensive green roof systems from Germany and Japan, which consist of layers of materials with different functions (see Section 3.1 for details).

2.1.1 Built-in and modular green roofs

According to the basic construction method, green roof systems can be divided into two categories: built-in green roofs and modular green roofs. Table 2.2 compares these systems. Figure 2.5 shows examples of built-in and modular green roof systems in Singapore, which are installed on the car-park roof of the housing estate. Some green roofs are rolled out like sod, some are pre-planted in boxes and some are installed layer by layer (Loh, 2009). Interlocking modular systems have recently been developed to suit particular site conditions (Hui and Chan, 2008; Velazquez, 2003) and the requirements in retrofit projects for existing buildings.

Figure 2.4 Extensive green roof systems from Germany (left) and Japan (right)

Table 2.2 Comparison of built-in and modular green roofs

Built-in green roofs	Modular green roofs
▪ Installed as a series of layers ▪ Usually require a longer installation period ▪ More complex and permanent ▪ Time is needed for on-site installation and growing ▪ Excess weight (180–450 kg/m^2) ▪ Complexity of maintenance ▪ Separate installation of green roof components ▪ Increase design opportunities, biodiversity and experience ▪ Require various subcontractors for design and installation	▪ Prefabricated off-site and pre-grown ▪ Usually require a shorter installation period ▪ Modular design, subdivided into standard interchangeable parts ▪ Ready-made flexible (vegetative mats into a woven fabric) or firm (metal or recycled plastic) trays or modules ▪ The essential components of the system are already combined ▪ Type of plants may be limited

Due to pre-planting, the modular systems are more expensive upfront. However, reduced maintenance and installation costs can help offset the initial investment. Individual trays make it easier for technicians to troubleshoot leaks or other roofing issues. The general benefits include:

- design simplicity and immediate roofscapes (instant greening)
- easy and time-saving installation
- off-site planting
- different types and depths of growing medium
- adaptive to all forms of irrigation
- adjustment and rearrangement after installation are easier.


Figure 2.5 (top) Examples of built-in and modular green roof systems in Singapore (on car-park roof of housing estate)
Left: Built-in green roof system
Right: Modular green roof system



Figure 2.6 (bottom) Examples of modular green roof systems
Left: Vegetated mat system
Centre: Tray system
Right: Sack system

2.1.2 Examples of modular green roof systems

Modular systems are commonly used in the form of trays of vegetation in a growing medium, which are grown off-site and simply placed on the existing roof to achieve complete coverage. The drainage, soil substrate or growing medium and the plants are self-contained within the module, with varying dimensions. In effect, these three main components of a green roof are replaced by a fully planted module. When interlocked, they offer continuous roof drainage and coverage.

Modular green roof systems can be in different depths of growing medium, typically ranging from 45 mm to 300 mm. One particular form of modular green roof systems is the pre-cultivated vegetation blankets that resemble green roof tiles and are available in different dimensions. Figure 2.6 shows three examples of modular green roof systems including vegetated mat, tray and sack systems.

Figure 2.7 Podium green roof in Hong Kong

2.2 Green roofs for new buildings

There are some advantages to applying green roof systems to new buildings over existing buildings (Urbis Limited, 2007). First, costs can be saved in the design stage since the systems can be part of the existing contract. Second, roof slabs can be designed to take heavier soil depth loads. Third, irrigation and water supply can be built into the roof from the start. Fourth, utilities can be arranged to maximise green roof area. Fifth, barrier-free access (e.g. lifts) can be incorporated into the design if public access is considered. Finally, extended side walls to protect green roofs from excessive wind may be incorporated at the design stage.

In Hong Kong, intensive green roofs are commonly found in the form of podium gardens, which provide valuable, functional open space for human use (see Figure 2.7 for an example). Some new commercial and residential buildings have sky gardens or greenery on the upper floors or at the top of the building. Many public open spaces are also built either wholly or partially on structure. Figure 2.8 shows some examples of green roof systems in Hong Kong.

However, the application of extensive green roofs and other urban greening technologies is still limited in Hong Kong for various reasons. For instance, there is no government regulation on compulsory use of green roofs on new projects for private developers; and there are technical difficulties related to installing green roofs in existing buildings. However, these issues have been improved by the introduction of green building incentives (see Section 4.5) and the promotion of green government buildings (DEVB and ENB, 2009). Extensive green roofs seem to be better suited to retrofitting projects, which have their own technical constraints and are not yet well established in Hong Kong. Therefore, more information on extensive and modular green roofs is provided in these guidelines.

2.3 Green roofs for existing buildings

For wide-scale installation of green roofs to take place in a way that has a significant impact on the reduction of the UHI effect or rainfall runoff at a sub-catchment (district) level, the majority of green roofs will need to be retrofitted (Liu, 2011). It should be noted that green roofs on existing buildings through retrofit projects is an important consideration for urban cities because existing buildings constitute a major portion of the building stock. Roof greening is an effective way to maximise the greenery of built-up areas (CEDD, 2010). When applied to these buildings, the green roof design will be limited to the loading capacity of the existing roof unless a higher initial cost is paid to upgrade the structure. Thus, a suitable green roof system (usually lightweight) and proper design arrangement are important for existing buildings.

Owners of commercial and institutional buildings normally repair or refurbish roofs during the lifetime of the building (typically every 15–20 years) and do not require planning permission to do this. In most situations for commercial or institutional buildings, retrofitting of green roofs is technically feasible. This presents an opportunity for the community to encourage the building owner to green the roof. This may be achieved, to some extent, through education alone (when the building owner becomes aware of energy savings and other benefits, he or she may decide to invest

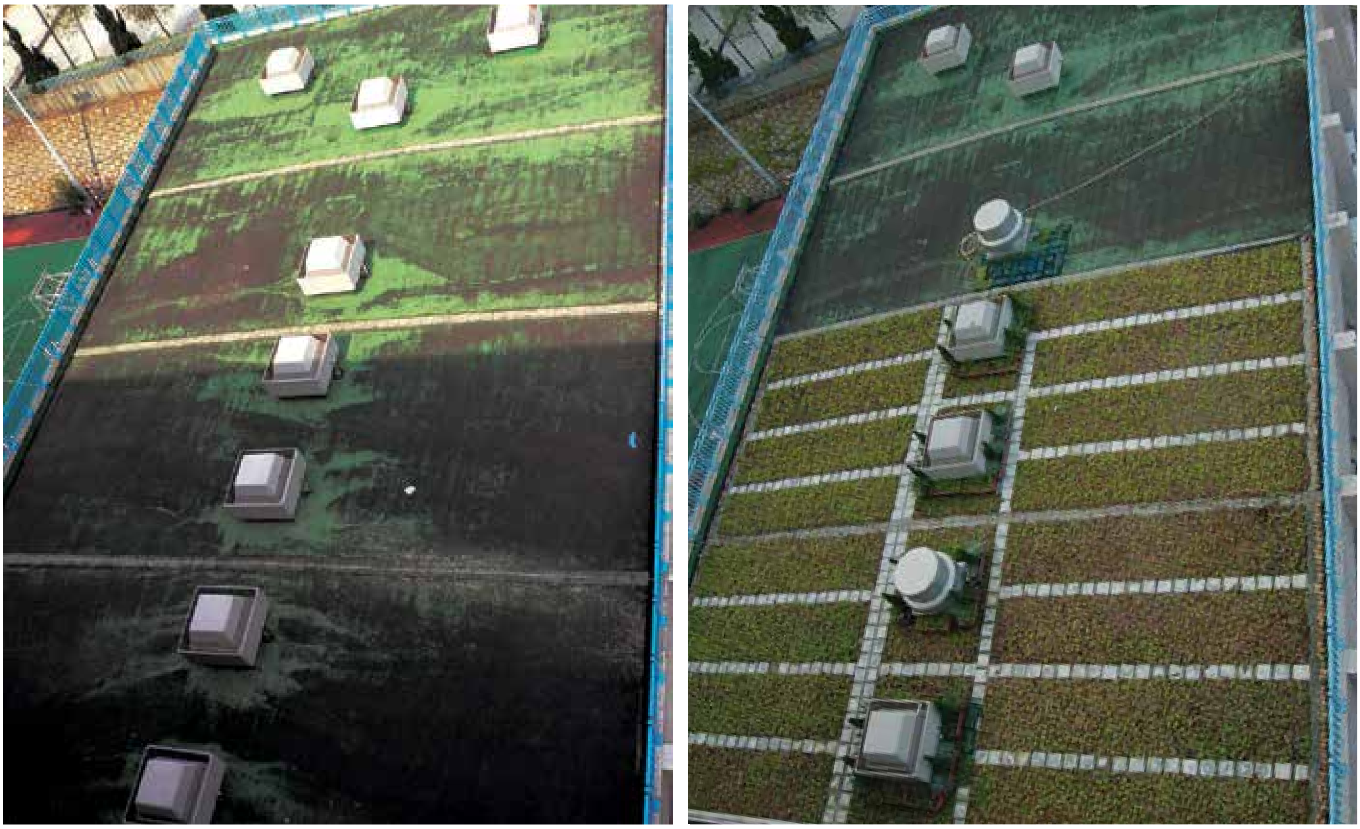
Figure 2.8 Examples of green roof systems in Hong Kong
Top left: Ocean Park Hong Kong
Top right: EMSD Headquarters
Bottom left: Parklane, Tsimshatsui
Bottom right: A school in San Po Kwong

in a green roof), however the additional cost associated with purchasing and installing green roofs may deter some owners. In the short to medium term, it may be necessary to establish a subsidy or grant scheme in order to encourage green roof installation. In the longer term, as energy prices increase, reductions in building running costs and extension of roof life may be incentive enough.

When considering a retrofit project, the age and condition of the existing building and roof will affect the feasibility of a green roof. Roof-top utilities and plant space can constrain the possible area of green roofs. The current structural loading and building requirements may limit growing medium depth and type of vegetation. Additional rooftop water points and new drainage points may need to be installed.

If access to the roof may be difficult (e.g. only by using cat ladders), additional safety devices may need to be installed. In some situations, barrier-free access may be impossible to retrofit. Figure 2.9 shows an example of a retrofit project with a green roof on a school building in Hong Kong (see also Sections 5.6 and 5.7).

Figure 2.9 Retrofit project with a green roof on a school building in Hong Kong
Left: Before retrofit
Right: After retrofit with a green roof system



3 Definitions

A 'green', 'living' or 'vegetative' roof is a system where vegetation is incorporated into a roof, usually supported by a growing medium, filter sheet, drainage/reservoir layer, root barrier and waterproof membrane (FLL, 2008). Green roofs can block solar radiation, and reduce daily temperature variations and thermal ranges between summer and winter. NRCA (2009) defines green roof system as: 'a roof area of plantings/landscape installed above a waterproofed substrate at any building level that is separated from the ground beneath it by a man-made structure'.

A green roof development involves creating vegetated space integrated structurally on top of a man-made structure (Urbis Limited, 2007). The word 'roof' in this context refers to any continuous surface designed for the protection of inhabitants from the elements, whether open or closed on the sides. The vegetated space may be below, at or above grade, located on a podium deck, a 'sky garden' on an intermediate floor level, or at the very top level of the building, but in all cases the plants are not planted in the ground.

Freestanding containers and planters placed on top of a roof are not generally considered to be true green roofs, although this is an area of debate. However, there are circumstances, particularly in retrofitting, where use of planting in pots or planters may provide a practical solution and an acceptable greening effect.

3.1 Structure of green roofs

A green roof requires appropriate levels of each of the following in order to flourish: sunlight, moisture, drainage, aeration to the plants' root systems and nutrients. Figure 3.1 shows the typical structure of an extensive green roof (Hui, 2009). It comprises a waterproof membrane, followed by a root barrier, a layer of insulation, a drainage layer, the growing medium or soil substrate and the plant material. A shallow layer of gravel or pebbles are placed from 0.5–1 m within the outside perimeter of the roof, providing additional drainage, fire control and access to the roof for maintenance. Other components and accessories of green roofs may include insulation, membrane protection layer, leak-detection system, ponds and pools, irrigation system, walkways, curbs and borders, railings and lighting.

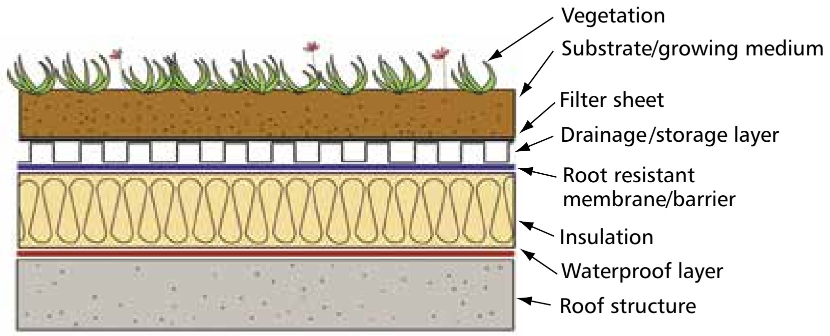


Figure 3.1 Typical structure of extensive green roof (Hui, 2009)

The thermal insulation layer is optional and will be needed according to the climatic conditions and local thermal efficiency regulations. Table 3.1 describes the functions of the major components of the green roof.

Table 3.1 Major green roof components and their performance characteristics

Layer	Functions	Performance characteristics
Vegetation	Various types of vegetation could be chosen for intensive or extensive systems. Shrubs, coppices and trees can be found in intensive systems; while grasses that require low maintenance and are capable of self-propagation are usually used in extensive systems.	▪ Appearance ▪ Species diversity ▪ Indigenous species ▪ Plant characteristics ▪ Perennials or annuals ▪ Water consumption pattern
Substrate/growing medium	An engineered soil replacement that contains a specified ratio of organic and inorganic material; specifically designed to provide green roof plants with the air, water and nutrient levels that they need to survive, whilst facilitating the release of excess water.	▪ Weight (kg/m^2) ▪ Resistance to wind and water erosion ▪ Free from weeds, diseases and pests ▪ Appropriate water retention ▪ Appropriate supply of nutrients
Filter sheet	A geotextile that avoids fine soil or other substances getting into the drainage layer, to ensure its efficiency and maintain permeability.	▪ Weight (kg/m^2) ▪ Tensile strength (kN/m^2) ▪ Flow rate under hydraulic head of 10 cm (l/s per m^2) ▪ Effective pore size (m^2) ▪ Penetration force (N)
Drainage/storage layer	Made of hard plastic, polystyrene, foam, coarse gravel or crushed recycled brick; acts as a water reservoir to retain water to certain level and can drain out excess water.	▪ Water storage capacity (l/m^2) ▪ Filling volume (l/m^2) ▪ Flow rate (l/s per m^2) ▪ Weight (dry) (kg/m^2) ▪ Compressive strength (kN/m^2)
Moisture mat	A geotextile blanket, available in varying thicknesses (typically 2–12 mm); provides an additional measure to retain water; protects the waterproof membrane during the installation.	▪ Water storage capacity (l/m^2) ▪ Thickness (mm) ▪ Weight (dry) (kg/m^2) ▪ Tensile strength (kN/m^2)
Root resistant membrane	This can be a chemical agent of a physical root barrier. It is essential in the system to prevent plant roots from penetrating into the roof structure, which would lead to water leakage problems and even damage to the building structure.	▪ Density (kg/m^3) ▪ Tensile strength (N/mm^2) ▪ Elongation to break (%)

3.2 Green roof guidelines and standards

Germany and Japan are technically more advanced than Hong Kong and have done a lot of pioneering work in supporting roof greening with various innovations.

3.2.1 Germany

The FLL, established in 1975 as a not-for-profit organisation, is the Research Society for Landscape Development and Landscape Design (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.) (www.fll.de). It is a key player in the development of the green roof movement in Germany (Lawlor, *et al*., 2006). When the green roof market boom first took off in Germany, many unqualified green roof companies surfaced, leaving behind a legacy of poorly constructed green roofs. The FLL guidelines (FLL, 2008) have been highly successful in setting quality standards for green roof systems throughout Germany. Home and building owners are guaranteed a sound product when purchasing green roof systems and products designed according to the FLL guidelines.

The FLL guidelines cover types of green roofs, various vegetation types, requirements for the building technique, green roof procedures and upkeep and maintenance. They are available in German and English, but the content applies to the middle European climate region and the common German green roof system build-up. The guidelines and related standards have formed the basis of similar standards in many countries that have adopted green roofing standards. The FLL has also developed specific tests to determine the root resistance of waterproofing materials and root-barriers, to evaluate water-holding capacity of growing medium, and to estimate maximum weight of green-roof media.

3.2.2 Japan

In Japan, the Organisation for Landscape and Urban Green Technology Development (known as Urban Green Tech), set up in November 1990 (www.urbangreen.or.jp), is responsible for promoting urban greenery and green spaces. It has developed and published some important guidelines on roof-top and wall greening (written in Japanese) (Organisation for Landscape and Urban Green Technology Development, 1996; 1999; 2000):

- *Neo Green Space Design, Volumes 1 to 4* (1996)
- *Guide to Roof and Wall Green Technologies* (1999)
- *Green Roof Q&A* (2000)
- *Green Wall Q&A* (2006).

With the support of the Ministry of Land, Infrastructure and Transport and the Ministry of the Environment in Japan, Urban Green Tech has organised annual competitions on specialised greening technology for rooftops, wall facings and new green spaces since 2002. It also coordinates research and development work, conferences and incentive schemes on urban greening.

These financial incentives are important as they offset the higher costs of green roof technology. However, technology costs will fall as green roofs are more widely implemented.

Like Germany, Japan has a mature green roof market with some green roof suppliers and companies prepared to provide planning guides and information to practitioners. The local provincial governments have also developed requirements and standards, together with incentive schemes. These help to ensure the ultimate quality of the green roof systems and to promote their use. It is interesting to note that some of the Japanese green roof guidelines and documents have been translated into Chinese and they are now being referred to and studied in mainland China and Taiwan.

3.2.3 Other countries

Germany's and Japan's guidelines and standards are useful references as they give comprehensive information and practical considerations for general application to green roof systems. In recent years other countries and cities have also developed guidelines, manuals and codes for green roof systems to suit their own needs (see Appendix A3 for a summary).

Besides green roof guidelines and codes, some countries have also developed technical testing standards in order to specify the quality and requirements of green roof systems and components. Appendix A4 gives a list of the technical standards for green roofs. Whether green roof guidelines exist or not, the complementary country regulations and guidelines must also be considered. These guidelines can include building technique (e.g. load-bearing capacity, wind uplift protection, fire protection, temperature, noise protection, etc.) and the roof technique (waterproofing material and installation, upstands, slope, drainage, etc.). Consideration must also be given to any existing regulations and guidelines for garden and landscape architecture (e.g. soil and plants, lawn, seed mixture, upkeep and maintenance works, etc.).

4 Planning requirements

Green roof projects will all vary. When creating and planning a green roof, the first consideration is to establish its objectives and functions. For example, will it be used for environmental and green building benefits; or will it also be accessible to people to use as a recreational amenity? Crucial factors are the load-bearing capacity of the roof construction and the choice of appropriate green roof build-up.

Identifying the scope of work is essential when considering a green roof installation. Project goals need to be established, with a plan for implementation, financial constraints, timeline and intent of the project. Determining factors for design team selection include new or retrofit construction, budget, size of the project, construction time, system type and category, and programmed use. Appendix A5 shows checklists for green roof planning, which can help people to consider the key issues.

4.1 Functions and effects

The primary functions that a specific green roof is required to perform will have a profound effect on its overall design. For example, a green roof designed for agricultural uses may look very different from one with the main purpose of brightening a hospital courtyard or as an educational tools for schools. Each individual green roof project will differ according to its use, depending on whether it is created for ecological, recreational, economic or aesthetic purposes.

Along with the question of aesthetics are inherent differences in the required depth of growing medium, the ongoing maintenance programme and overall cost. This is not to say that a green roof designed to retain rainwater cannot or should not also be aesthetically pleasing; it can be both, but limiting factors in the budget or the building structure, among others, may concentrate the focus on one of these functions.

The location of the green roof plays an important role in the design process. The height of the roof, its orientation and its exposure to wind, sun and shading by surrounding buildings will all have an impact. Views to and from the roof may also determine where certain elements are located for maximum effect. If the green roof can be designed as a roof garden for public access, other social functions can be considered, including urban farming, education, leisure activities and horticultural therapy. The stakeholders' involvement and support are crucial for developing these functions.

4.2 Structural loading

Additional loading is one of the main factors in determining both the viability and the cost of a green roof installation. If a green roof is part of the initial design of the new building, the additional loading can be accommodated easily and for a relatively minor cost. However, if a green roof is installed on an existing building, the design will be limited to the carrying capacity of the existing roof, unless the owner is prepared to upgrade the structure, which can be a significant investment. Hence, the critical factor in deciding what type of greening to use and how to cultivate the site is the design loads of the system.

4.2.1 Typical loading

Loads can be classified into two types: dead and live (or imposed) loads. Dead loads in a green roof, also known as constant loads, consist of super structural components such as membranes, non-absorptive plastic sheet component, metallic layers, fabrics, geo-composite drain layers, growing medium, granular drainage media and plant materials. Live (or imposed) loads in a green roof system (excluding that of construction activities) are defined as the weight of transient water that can be held temporarily in the granular drainage materials layer and composite drainage layer, i.e. the transient water held due to a continuous rainfall or irrigation until the drainage layer reaches saturation point. Architectural elements such as walkways, pavements, walls, water pools, play areas, pergolas (shaded walkways), large-scale bushes and trees, in addition to live loads of construction activities and wind loads, are calculated separately. The typical structural loading for extensive green roofs is about 80–150 kg/m^2 and for intensive green roofs is about 300–1000 kg/m^2 (remark: 1 kPa ≈ 100 kg/m^2). Tables 4.1 and 4.2 give the typical weights of green roof substrate materials and common building materials.

Table 4.1 Weight of green roof systems and substrate materials

Typical green roof systems	Weight of a 1 cm layer (kg/m^2)
Extensive—sedum	11
Extensive—wild flower and sedum	13.5
Intensive	14–16
Substrate materials	**Weight of a 1 cm layer (kg/m^2)**
Gravel	16–19
Pebbles	19
Brick (solid with mortar)	18
Sand	18–22
Sand and gravel mixed	18
Topsoil	17–20
Lava	8
Light expanded clay granules (LECA)	3–4

Adapted from: Dunnett N and Kingsbury N (2008) *Planting Green Roofs and Living Walls* (revised and updated edition) (Oregon: Timber Press).

Adapted from: Dunnett N and Kingsbury N (2008) *Planting Green Roofs and Living Walls* (revised and updated edition) (Oregon: Timber Press).

Table 4.2 Weight of common building materials

Materials	Weight (kg/m³)
Stone (granite, sandstone, limestone)	2300–3000
Concrete (precast)	2100
Concrete (reinforced)	2400
Concrete (lightweight)	1300–1600
Hardwood timber	730
Softwood timber	570
Cast iron	7300
Steel	8000

4.2.2 Structural analysis and design

Structural load-bearing capacity will determine the access, function and type of green roof, growing medium type and depth, plant selection, and replacement and repair strategies. The structural analysis should consider the waterproofing membrane, plant weight at maturity, fully saturated growing medium and drainage layers, and weight of all components including dead and live weights for all phases of the green roof. Spot loadings generated by large-scale bushes, trees and structural components will need to be calculated separately. The weight of every layer in a green roof system is determined at the point of maximum water capacity, including materials and stored water. Typical wet soil weighs approximately 1600 kg/m³, which is quite significant. Some green roof suppliers have developed various types of lightweight growing media in order to reduce the overall weight of the green roof system.

As different types of green roofs require differing loading capacity, it is possible to mix types of roof on one installation to accommodate the structural load. For instance, heavier materials, such as trees, can be placed on higher weight-bearing areas, such as columns or roof perimeters. This is especially important in retrofit projects where it may be necessary to be creative in the location and use of heavier structures. A thorough analysis of the roof structure may reveal areas where point loading can be increased, perhaps over a column or along a bearing wall, thus allowing for a combination of extensive and intensive (or semi-extensive) system, with specific areas for deeper growing medium and larger plants. Building owners, tenants and building managers should be made aware of the roof's loading restrictions, through a plan or as part of a maintenance manual, to avoid future improper relocation or additional plantings in areas that cannot accommodate the weight.

4.2.3 Practical considerations

In Hong Kong, the *Code of Practice for Dead and Imposed Loads* (BD, 2011c) should be applied to evaluate the likely structural loading. The weight of roofing such as waterproofing membrane, protective screed and tiles should be calculated from the weight of the component materials and their geometry, such as the thickness and area. Where a roof is to be provided with greenery, the weight of soil, waterproofing and drainage system, and plants for greenery should be taken as dead loads. The uniformly distributed load and the concentrated load should be considered separately.

Green roofs can be installed on commercial or residential buildings, as well as on underground structures. For existing buildings, structural integrity of the building must be verified before considering retrofitting the building with a green roof. For both existing and new constructions, it is essential that a multidisciplinary team of structural engineers, building services engineers, architects and landscape architects are involved early in the process to ensure that the building's structural characteristics and site conditions are appropriate for green roof installation.

Understanding structural load (dead and live loads) during implementation is especially important. Determining structural loading capacity uses a combination of dead loads. During construction, the temporary placement of heavy components such as trees, pallets of stepping stones, growing media, concrete cast-in-place planters, walls and furniture needs to be carefully planned and calculated. Carefully staging delivery and installation of growing media is recommended to keep labour costs down and ensure the schedule stays on track.

4.3 Accessibility and site conditions

The accessibility of the roof is a critical component of any green roof installation, not only for installation and ongoing maintenance, but also for bringing up materials, soil and plants. The success of a green roof depends on the ease and safety of access during and after installation, whether for frequent visitors or occasional maintenance.

4.3.1 Green roof accessibility

All green roofs require some degree of accessibility. Some green roofs might only be accessible for maintenance and other green roof gardens are designed specifically for daily use and high traffic volumes of visitors and users. Types of access may be a lift, stairs, a stairwell with doorways or a hatch. During the design phase of the project, access for installation and maintenance must be included and meet job site safety standards and building regulation requirements.

If the green roof is designed for public use, access and exiting of the roof should comply with relevant safety and security requirements through adequate vertical transportation systems and staircases. Roofs that are fully accessible to the public will require more safety concerns, such as guard rails, lighting, fire safety and disabled access. The construction requirements for buildings might also have to be adapted to the specific needs of disabled and elderly people.

With a new building, the design of internal stairs or an extra lift stop in the planning stages is easy and relatively inexpensive; to retrofit an existing building can become costly. Where a lift does not go to the roof, material will have to be transported by hand up stairs and utility ladders, or hauled up with a crane, both of which can result in additional labour and equipment costs. An interior ladder or staircase may be safer than one attached on the outside of the building, and access through a 'man door' is preferable to a small roof hatch. If the green roof is designed for use by tenants or the general public, questions of access and of exiting are taken to another level altogether, from mere convenience to strict standards of safety and security as regulated by the local building regulations.

4.3.2 Site conditions and roof space

For successful establishment and long-lasting vegetation, it is crucial to consider the local site conditions. Table 4.3 shows the major considerations of site conditions for green roofs (FLL, 2008). The general climate of the area and the specific microclimate on the roof must be considered.

Table 4.3 Major considerations of site conditions (adapted from FLL (2008))

Climate and weather	▪ Regional climate ▪ Local microclimate ▪ Pattern and amount of rainfall ▪ Average exposure to sunshine ▪ Shadowing effect of the surrounding buildings ▪ Any incidence of periods of drought ▪ Direction of prevailing wind ▪ Airborne contamination ▪ Whether it is located extremely close to sea or high on a mountain
Structure	▪ Design loads for the roof structure ▪ Exposure of roof surfaces ▪ Gradient of slope of the roof surfaces ▪ Existence of any major plants and exposed pipework on the roof ▪ Areas exposed to the sun and shaded areas ▪ Deflection of precipitation by the structure ▪ Wind flow conditions and wind uplifting effect
Plant	▪ Current drainage arrangements on the roof ▪ Water requirements ▪ Power supply requirements (for lighting and equipment)

The vegetation layer and plant communities can be modified according to site conditions, whereas the roof height, roof slope and the predominant climate are fixed. Additional considerations include: sunlight and wind exposure, air pollution, variation of temperature, local moisture conditions and access to water and electricity supply. Even on one roof, various microclimatic conditions can occur. For existing buildings, if the roof is in need of replacement or major repair, particular care must be taken to prevent water leakage and ensure waterproofing.

If the roof space is also being used for other utilities (pipes, plant rooms, etc.), then sufficient space for an area of mechanical plants, access pathways and safety railings is important in the roof planning and design. Where plant rooms are required for the building services systems, two approaches can be taken. The area of plant room can be reduced to a series of storage areas on the roof, surrounded by the green roof technologies and green planting including vegetated green walls. The second approach is to incorporate all the plant-room activities into an additional floor at the top of the building and then cover the entire plant room with a green roof.

In densely populated cities like Hong Kong, many existing or planned roof spaces in the urban area offer potential for development, as green roofs are shaded from the sun by surrounding tall buildings for much of the day. This influences plant selection and growth. Appendix A6 shows a sun path diagram for Hong Kong, which can be used to evaluate the solar access and daylight availability.

Hong Kong also has a high building density and the high-rise buildings usually have very limited roof area (Hui and Chan, 2008). It is usually more effective to apply green roofs to the top of medium- or low-rise buildings/structures or the intermediate podium roofs. This means that occupants from surrounding tall buildings can enjoy the green roof and appreciate the application.

4.4 Waterproofing

High-quality waterproofing is a critical issue for the success of a green roof. Suitable arrangement and design of waterproof membrane can reduce the reparation costs and extend the roof's life.

One of the most important components of the green roof system is the waterproofing/roof membrane. Green roofs should not be installed until waterproofing has been inspected and tested. For an existing building, the membrane should be carefully inspected to determine if it needs to be repaired or replaced before the installation. Many suppliers of green roof systems will not provide a warranty on the green roof system if new membranes are not applied. The normal 10- to 15-year re-roofing cycle provides a window of opportunity to investigate the potential of applying a longer lasting green roof.

To protect the membrane, it is important to minimise the number of penetrations and transitions, and all the expansion joints must be accessible. Low points should be levelled to avoid water ponding. If the membrane —existing or new—contains bitumen or any other organic material, it is crucial to maintain a continuous separation between the membrane and the plant layer, since the membrane will be susceptible to root penetration and micro-organic activity. Some of the new membranes developed specifically for green roof applications, although still bituminous, now contain a root-deterring chemical or metal foil between the membrane layers and at the joint/seam lines to prevent root damage. The chemical makeup of the membrane must also be compatible with the system components with which it will be in direct contact.

Although the green roof will retain much of the rain that falls on it, maintaining proper drainage on the roof is still very important. Parapets, edges, flashing and roof penetrations made by skylights, mechanical systems, vents and chimneys must be well protected with a gravel skirt and sometimes a weeping drainpipe. If the drainage layer is too thin or if the routes to the roof drains become blocked, leakage of the membrane may occur, due to continuous contact with water or wet medium. The growing medium itself may sour, causing the plants to drown or rot.

As mentioned in Section 3.1, the root-resistant membrane or barrier can protect the waterproofing membrane and/or insulation layer during installation of the green roof. Many different materials can be used for this purpose including synthetic thermoplastic, recycled foam/rubber mats, polyethylene net composite and non-rotting fibre. The material should add little weight to the green roof system. However, it may not be required if the roof is rigid and strong enough.

4.5 Green building credits

Green building assessment methods, such as BREEAM (www.breeam.org), LEED (USGBC, 2009) and BEAM Plus (BEAM Society, 2010a; 2010b), are becoming more popular and important. For example, in the USA, the use of green roof systems has been encouraged by the need to obtain credit points for LEED; green roofs can contribute to the credit rating of developments assessed under such schemes, which can encourage clients to support green roofs. A green roof can also be a highly visible way for building development to draw attention to its environmental or sustainability 'credentials', which may contribute to increased property value. In the commercial sector, for example, it is anticipated that buildings that compare unfavourably to their market peers in sustainability terms will be at risk of accelerated value depreciation and earlier physical obsolescence.

4.5.1 LEED and BEAM Plus

Building designers can pursue sustainable design and earn points towards project certification. Green roofs can assist in gaining credits under several environmental criteria in the green building assessment. Tables 4.5 and 4.6 give examples of credit points (main criteria impacts and secondary credit impacts) relating to green roof systems in LEED (2009 version) and BEAM Plus, respectively. They show that the greening technology has significant implications for the assessment results, which should promote greenery to developers and building professionals.

Table 4.5 LEED 2009 credit points of green roof systems (from USGBC (2009))

LEED criteria impacts	Points
Sustainable sites (SS)	
Credit 5.1 Site development—protect or restore habitat	1
Credit 5.2 Site development—maximise open space	1
Credit 6.1: Stormwater design—quantity control	1
Credit 6.2: Stormwater design—quality control	1
Credit 7.2: Heat island effect—roof	1
Water efficiency (WE)	
Credit 1: Water efficient landscaping	2–4
Energy and atmosphere (EA)	
Credit 1: Optimise energy performance	1
Materials and resources (MR)	
Credit 4: Recycled content (roof components)	1
Credit 5: Local/regional materials	1

Secondary credit impacts	Points
Water efficiency (WE)	
Credit 2: Innovative waste water technologies	2
Credit 3: Water use reduction	2–4
Innovation in design (IN)	
Credit 1: Innovation in design	1–5

Table 4.6 BEAM Plus credit points of green roof systems (extracted from BEAM Society (2010a))

BEAM Plus criteria impacts	Points
Sites aspect (SA)	
Prerequisite: Minimum landscape area	**Required**
SA 5: Ecological impact	1
SA 7: Landscaping and planters	1–3
SA 8: Microclimate around buildings (roof)	1
Materials aspects (MA)	
MA 7: Recycled materials (roof components)	1
Credit 5: Local/regional materials	1–2
Energy use (EU)	
EU 1: Reduction of CO_2 emission	1–15
EU 2: Peak electricity demand reduction	1–3
Water use (WU)	
WU 1: Water efficient irrigation	1
WU 6: Effluent discharge to foul sewers	1

Secondary credit impacts	Points
Water use (WU)	
WU 4: Water recycling (rainwater)	1–2
Innovations and additions (IA)	
IA 1: Innovative techniques	1–5

4.5.2 Green building incentives

Developing a property, for a new building or in a retrofit situation, often requires a certain percentage of green space, depending on the site location and the occupancy of the building. Local planning and zoning may qualify a green roof as green space or landscaped open space. This could permit the developer to use more of the property at grade, or to qualify for density bonus. If the green roof is accessible to tenants, it may also qualify as an amenity space for the building, with no loss of gross floor area within the building envelope. Moreover, a green roof may be used as a consideration on environmentally sensitive sites or with environmentally sensitive community groups.

Government policies and standards influence the promotion of green roofs in the public and private sector in both direct and indirect ways. For example, Hong Kong Government has developed incentives and guidelines to promote green and sustainable buildings by granting exemptions of gross floor area (GFA) and site coverage (SC) to building developers, and by encouraging sustainable design features as well as green building assessment (using BEAM Plus) in building projects (BD, LandsD and PlanD, 2011a; 2011b; BD, 2011b). Building features that can improve the built environment, such as communal podium gardens and sky gardens, are accepted for the incentives (BD, 2011a; 2011d; BD, 2010). Site coverage of greenery and BEAM Plus certification are pre-requisites for granting the GFA concessions. For government buildings, building developers must consider use of green initiatives or comply with BEAM Plus standards where applicable or feasible (DEVB and ENB, 2009). Under these policies, the use of green roof systems is encouraged.

5 Design considerations

Green roofs can be designed to be a beautiful landscape and functional green space. They can also be designed to generate urban agriculture and promote sustainable technologies. For a successful green roof, the design and selection of growing medium, irrigation systems and plantings must be carried out systematically.

5.1 Landscape design

To achieve quality landscaped areas for green roofs, it is important to study the components of landscape design, which include the practical, aesthetic, horticultural and environmental issues of the softscape and hardscape. 'Softscape' refers to the elements of a landscape that comprise live, horticultural elements, such as flowers, plants, shrubs, trees, flower beds, etc. The purpose of softscape is to give character to the landscaping, create an aura and ambience, and reflect the sensibilities of the inhabitants. In contrast, 'hardscape' represents inanimate objects of a landscape, such as pavers, stones, rocks, etc. When designing a green roof, combining the colour and beauty of plants with architectural pavers can yield aesthetically pleasing results.

In non-modular green roof systems, the planting medium is supported by the drain layer and contained at the perimeter by a metal or plastic barrier or the roof parapet. In modular systems, containment refers to actual plant containers. For proper edge treatment, the vegetation should be separated from the parapet or edge by a hard paving of a width of at least 500 mm. Figure 5.1 shows an example of landscape design for a green roof system.

Figure 5.1 Landscape design for a roof garden in Harvard University, Boston, USA
Credit: Stephen Lee and Richard Burck Associates, Inc

Table 5.1 describes the major considerations of landscape design for green roof systems.

Table 5.1 Major considerations of landscape design for green roof systems

Issue	Design consideration
Water use	▪ Aim to be sustainable in water use. ▪ If possible, harvest rainwater and reuse for irrigation. ▪ Where appropriate, use greywater technology.
Landscape materials	▪ Soil profile to include free-draining, sand-like product, clay minerals. ▪ Incorporate sustainable landscape materials wherever possible (this reduces the ecological footprint). Consider a specially formulated growing medium that includes a recycled component locally available, such as crushed brick. ▪ Use light-coloured, wind-resistant landscape mulches to help reduce soil temperatures and reduce evaporation from soils. Examples include light-coloured 10 mm gravel.
Site ecology	▪ If practical, and if original soils have not been adversely affected, aim to restore some of the existing ecology to the site—this will improve site biodiversity. ▪ If possible, link site to existing open spaces and reserves to create habitat corridors.
Choosing plants	▪ On green roofs, plants will be subjected to more extreme conditions than those in a garden bed at ground level. They will be subjected to higher temperatures and windier conditions, leading to rapid water loss and frosts during the cooler months, so plants need to be chosen well.
Maintenance	▪ Ensure a landscape management plan is in place to protect investment in the green roof/wall technology. Maintenance and replanting are vital in maintaining healthy green roofs.
Monitoring	▪ Include a proportion of the budget for weather-station monitoring equipment.

For intensive (or sometimes semi-intensive and extensive) green roof applications, there are a number of hardscape paving materials that can be used to provide a walkway or sitting area. Precast concrete architectural pavers are commonly used and are installed in an open joint assembly (supported at the four corners on spacer tabs or pedestals). This method of installation allows for water to drain below the wearing surface rather than pond on it; this eliminates the likelihood of dangerous pedestrian conditions, as well as possible heaving resulting from trapped moisture. In addition, the open joint assembly provides easy access to the assembly components and structure below, facilitating maintenance and future deck alternations.

5.2 Water supply and drainage

The number of water mains pipes and junction points required for watering, along with the sizes used, will depend upon local conditions and the structure involved. During the planning and design stage, water mains demand will need to be established by considering the local conditions and the form of cultivation to be used for the vegetation. Sometimes it is possible to collect the water outflow from the green roof for another use or even to irrigate itself.

5.2.1 Water supply and retention

Extensive green roofs with drought-resistant plant species only have to be irrigated during planting and installation maintenance over the first year. Once established, the vegetation is sufficient to be sustained by the annual rainfall (however, for some dry desert climates such as the Middle East, irrigation will be needed on a regular basis). In contrast, the requirements are more involved for intensive green roofs with lawn, shrubs, bushes or trees. An adequate number of precisely dimensioned hoses with automatic irrigation units make plant maintenance during drought periods more manageable. The water supply for roof gardens with no slope can be increased through additional dam-up irrigation. In order to lower the consumption of fresh water, roof gardens can also be irrigated with reclaimed rainwater or waste water.

Green roofs retain a high percentage of rainwater; excess water must be drained from the roof by surface roof drains, gutters or other drainage systems. Figure 5.2 shows the principles of the drainage/storage layer in an extensive green roof. The water-retaining capacity of the green roof system has to be adjusted to the average local precipitation. Proper roof drainage design should incorporate a minimum of two outlets, or an outlet and an overflow. Outlets should be kept clear of vegetation by installing a vegetation-free zone around them and a cover that stops light from entering the drain area. Inspection chambers may be required to ensure that outlets are kept free of blockages.

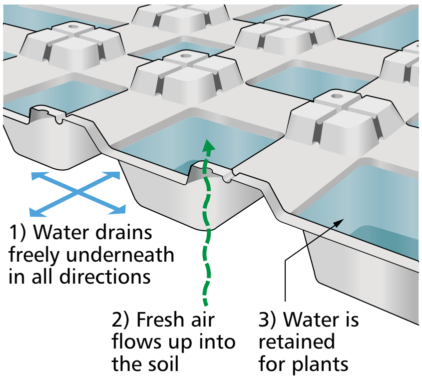


Figure 5.2 Principles of the drainage/storage layer in an extensive green roof

5.2.2 Drainage systems

Two drainage systems should be considered:

1. part of the green roof system (drainage layer)
2. part of the building (system of drains and pipes).

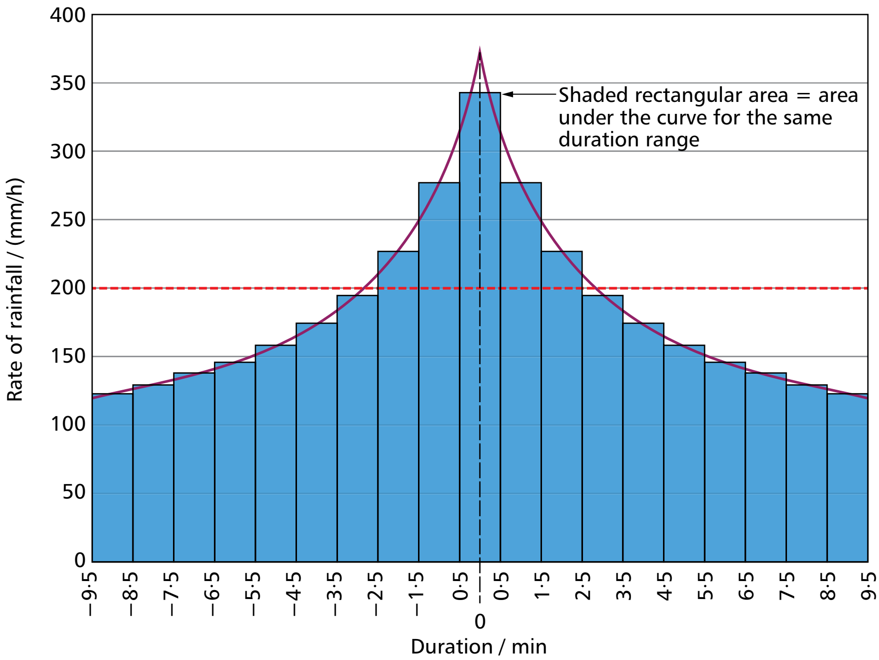


Figure 5.3 Design rainfall profile statistics for Hong Kong

Usually the information regarding design rainfall intensity and duration at that location will be used to design the roof drainage systems. Figure 5.3 shows the design rainfall profile statistics for Hong Kong. For a 20-year return period, the design rainfall intensity is taken as 200 mm/h.

Excess water should be drained by roof outlets and box/eaves gutters, which must be kept clear of vegetation to avoid blockage. Gravel can act as a separation barrier for plants. Vegetation-free zones should be installed at all perimeters and penetrations. These areas generally consist of a recommended 500 mm wide path of graved or architectural pavers. The purpose of a vegetation-free zone is to protect the roof flashings from plants' roots, as well as to provide wind-lift protection and ease of access to the flashings (if needed). Inspection chambers over all roof drains are recommended to stop plant growth in the drain. For very large green roof areas, vegetation-free zones are also recommended, to divide the roof into smaller zones in case of a leak or system failure.

To withstand constant moisture and the corrosive nature of some fertilisers, corrosive-resistant materials can be used. If only a portion of the roof is installed with green roof systems, the drainage both within and outside the vegetation area must be planned and designed properly. In addition to horizontal roof surfaces, the designer should ensure the drainage design accounts for vertical sheet flow from large facades due to wind-driven rains.

5.3 Wind design

Green roofs are often exposed to high wind levels. Wind can generate positive and negative pressure forces and friction, which impact on structures. A green roof must be able to withstand wind loading, especially in cases of strong wind. When designing and installing the green roof, safety measures against wind uplift must be considered. This is especially important when the green roof provides the load for a loose-laid waterproofing and root barrier. It should be noted that layers of green roofs are vulnerable to wind shear. The actual influence from the wind depends on the local wind zone, height of the building, roof type, slope, area (whether corner, middle or edge) and the substructure. Figure 5.4 illustrates the wind effect and wind uplift for green roofs.

5.3.1 Wind uplift and ballast

Wind loads can damage anything built on top of the roof, either during construction or after work has been completed. The following areas on the roof are most affected by the wind pressure uplift and require appropriate protection:

- corners: stress levels are very high
- edges: stress levels are high
- the central area: stress levels are low.

Wind pressure can vary across a roof, depending on location. At the

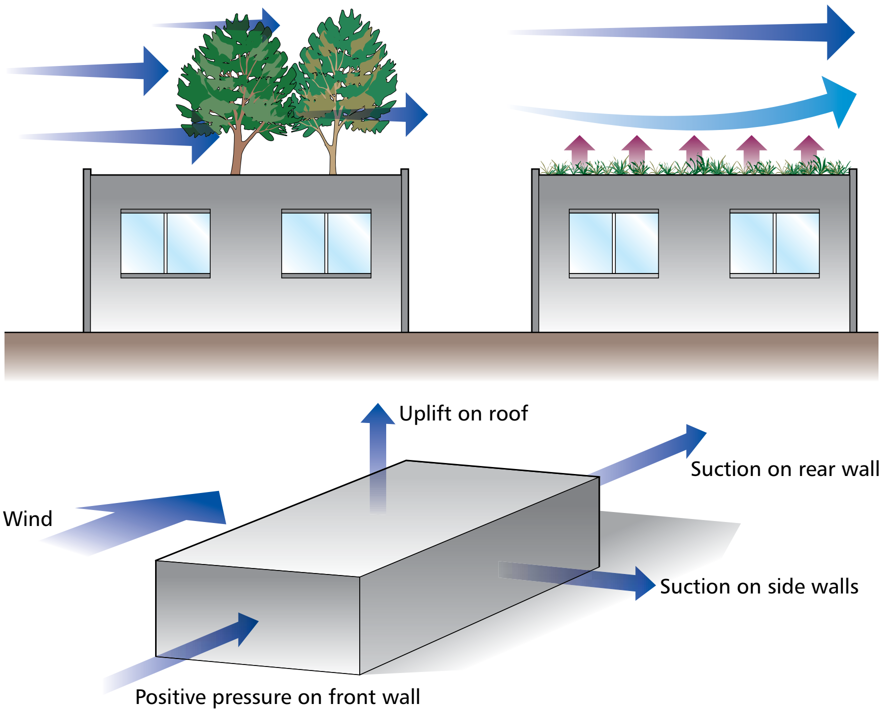


Figure 5.4 Wind effect and wind uplift for green roofs

centre of the roof, a thin layer of soil may be adequate. At perimeters and corners, high winds may necessitate the use of large stone ballast or multiple rows or precast pavers to prevent uplift. A strip of gravel, stones or pavers around the edge can prevent the wind damage; these also act as vegetation barriers. In general, taller structures have a greater risk of wind uplift. Ballasting requirements vary by building height, parapet height and wind design speed. SPRI (2010a) provides a method of designing wind uplift resistance of vegetative roofing systems.

In green roof systems, ballast is the weight provided by growing medium, stones or pavers to provide uplift resistance for roofing systems that are not adhered or mechanically attached to the roof deck. The ballast also provides drainage options when the roofing membrane is mechanically attached or fully adhered. When growing medium is installed and protected by vegetation that nominally covers the visible surface of the growing medium, or the growing medium is protected by a system to prevent wind erosion, the weight of the inorganic portion of the growing medium can be considered ballast weight. When modular trays that are filled with growing medium are covered by vegetation that nominally covers the visible surface of the growing medium, or the growing medium is protected by a system to prevent wind erosion, the weight of the inorganic portion of the growing medium can be considered ballast weight. Ballast can also consist of large stones, paver systems or lightweight interlocking paver systems.

5.3.2 Calculation of wind uplift design pressures

Low-rise buildings present fewer challenges in regard to positive or negative wind forces. A lower parapet design in a low-rise building may avoid potential air turbulence and help minimise uplift forces. High-rise buildings are exposed to increased wind pressure, resulting in higher positive and negative uplift forces. Increasing the parapet height can be an effective tool in moderating uplift forces.

Some green roof systems have been tested for wind uplift resistance. The wind uplift design pressures and wind rating pressures of the systems are determined. A minimum safety factor (e.g. 1.7) should be applied for wind uplift calculations based on appropriate wind uplift design pressures for the local design wind loads. The calculation is based on a dry condition (no water present in the growing medium, retention mat, drainage panel, etc.) and without the presence of any vegetation load.

Growing medium may be used as a secondary ballast material; that is, it may be used to ballast the loose-laid roofing components above the waterproofing membrane (i.e. drainage panel, retention mat, root barrier and insulation board) but not the membrane itself. When growing medium is used to ballast the loose-laid above-membrane components, the wind uplift calculations should use wind uplift design pressures, a dry condition (no water present in growing medium, retention mat, drainage panel, etc.), no vegetation and a minimum safety factor of 0.85.

5.3.3 Practical considerations

The growing medium on a green roof system can be prone to scour from wind and water action and therefore may not be a reliable source of uniform ballast for waterproofing components when provided in shallow depths. Growing medium typically contains aggregate materials, including crushed porous rock (e.g. pumice, expanded shale) or crushed clay brick, which can create a potential source of wind-borne debris similar to roof gravel. Although vegetation will provide a certain amount of wind shelter and the plant roots will help anchor the surrounding growing medium, it can take several growing seasons for the vegetation to become sufficiently established to protect the growing medium from wind action.

Pre-cultivated vegetated mats (rather than direct planting of plugs or cuttings) are sometimes used for green roofs (see Section 2.1). Where vegetated mats are installed, they should be anchored until the mat's root growth is sufficiently attached to the growing medium to adequately resist wind action (at least one full growing season). If pre-cultivated vegetated mats are to be used as ballast for the roofing membrane or other waterproofing elements, it is important to ensure that they are properly anchored or ballasted against wind forces based on a safety factor of 1.0.

Some cities, such as Hong Kong, often face typhoon and stormwater problems during the rainy season (Hui and Chu, 2009). Strong winds and heavy rainstorms could cause flooding and serious damage. The typhoon might blow away the vegetation and soil, so green roof systems that do not have proven wind uplift resistance must be well secured and protected. Green roofs should be able to hold and drain rainwater without creating pools of stagnant standing water.

5.4 Plant selection

Careful plant selection is essential to a green roof's success. Designs vary widely to incorporate different plant species and aesthetic functions, but the vegetative layer needs to be carefully considered for the conditions and the projected goals. Plant selection objectives depend on whether the design goals of the roof are for function, performance, education or aesthetics. Plant selection is also affected by growing medium, local conditions, available maintenance and appearance.

5.4.1 Typical plants

Green roof plants must be tougher and less nutrient-reliant than plants found in most parks. Other limitations are climate, structural design, maintenance budgets and the roofscape designer's imagination. In general, the most successful plants for green roofs can tolerate heat, cold, sun, wind, drought, salt, insects and disease. Low-maintenance, durable and drought-resistant plants are used for extensive green roofs, whereas a nearly limitless plant selection can be used for intensive green roofs.

5.4.1.1 Extensive green roofs

Plants for extensive green roofs have to survive intense solar radiation, wind exposure, drought, low-nutrient supply, extreme temperatures and limited root area. Suitable plant varieties grow in severe locations with little moisture and nutrient supply such as, dry mountain environments, coasts, semi-deserts or dry meadows. The main varieties are Sedum, Sempervivum and Saxifraga; all of which belong to the succulent species (see Figure 5.5 for some examples). The plants are able to store high amounts of water in their leaves, are stress resistant and recover easily from periods of drought. Other varieties such as Dianthus species, Asteraceae and ornamental grasses are also suitable for these conditions, but they will require more maintenance and irrigation. Wildflower turf is used in Europe to minimise irrigation and maintenance. It is important to consider plants that are native to the local conditions in order to support biodiversity.

5.4.1.2 Intensive green roofs

With an appropriate green roof system build-up and sufficient growing medium (with higher root penetration volume, nutrients and water supply), it is possible to grow sophisticated plant varieties on roofs. The selected plants need to be resistant to intense solar radiation and strong winds.

Figure 5.5 Examples of sedums used in extensive green roofs
Left: Sedum sinica
Centre: Sedum sarmentosum
Right: Sedum lineare

Vegetation with various plant varieties, such as perennials, herbs, grasses and trees, allow for a natural character on the roof. However, having a broader plant community increases the amount of maintenance required.

Factors for consideration when making plant selections include growth rates, nutrient requirements, sensitivity to pollution, wind resistance, solar exposure and drought tolerance. Location, wind, rainfall, air pollution, building height, shade and soil depth are all factors in determining what plants can be grown and where. A plant's ability to survive on a green roof is directly proportional to the amount of maintenance time and budget allocated to the project, particularly in the first two years when they are getting established.

5.4.2 Useful references and advice

Climatic conditions on a rooftop are often extreme. Unless one is willing to provide shading devices, irrigation and fertilisation, the choice of planting material should be limited to hardier or indigenous varieties of grasses and sedums. Root size and depth should also be considered in determining whether the plant will stabilise in 10 cm or 60 cm of growing medium. It is vital to know where the plants were previously grown and if the growing conditions were comparable to those on the roof to ensure their ability to adapt and flourish.

Urbis Limited (2007) has developed a plant selection matrix for green roofs (intensive and extensive) suitable to the Hong Kong condition. The list was derived from existing local knowledge and other overseas sources (such as Singapore) with humid climatic conditions similar to Hong Kong. Usually, trial planting and testing are needed in order to verify the suitability of the plant species. Other useful references for plant selection are listed here.

- *A Selection of Plants for Green Roofs in Singapore* (Tan and Sia, 2008).
- *Green Roof Plants: A Resource and Planting Guide* (Snodgrass and Snodgrass, 2006).
- *Living Wall and Green Roof Plants for Australia* (Perkins and Joyce, 2012).
- *Neo Green Space Design, Japan* (Organisation for Landscape and Urban Green Technology Development, 1996).
- *Planting Green Roofs and Living Walls* (Dunnett and Kingsbury, 2008).
- Plant lists: www.greenroofs.com/Greenroofs101/plant_list.htm.
- Plant resources: www.skyrisegreenery.com/index.php/home/plant_info/.

For low-maintenance application to new and existing buildings, sedums, which are commonly known as stonecrops, are often the core species for the green roof systems. They are a versatile and attractive ground cover plant belonging to the Crassulacaea family. Sedums are evergreen, self-generating, drought resistant and capable of withstanding extremes of climate. Requiring very little attention and no mowing or cutting back, they give excellent foliage colour and texture and are attractive to all kinds of insects and birds. Sedums are generally pest and disease free but like most plants, can suffer from aphids, mealy bugs, thrips or vine weevil, which can be controlled by biological means. Sedum plants are very economical when it comes to fertiliser; a slow-release, low-nitrogen granular fertiliser applied once a year (preferably in spring) is sufficient.

If designers specify the modular green roof system, they need to build-in time for the vegetation to mature (typically planted by the supplier or a nursery). Allowing horticultural experts to care for the plants from the start helps ensure the vegetation will continue to prosper once the system is installed, though no one can predict how the plants will react once placed on the roof.

5.5 Roof slope

In urban areas, pitched green roofs are a special attraction and planted sloped or pitched roofs look attractive due to their high visibility. Green roof systems for pitched roofs differ significantly from system build-ups for flat roofs. Plant selection and planting methods need to be adjusted to the relevant slope and exposure. Appropriate measures need to be taken to cope with the shear forces and soil retention. While the basic components of a sloped green roof are similar to that of a flat system, the building project team must pay particular attention to water management, erosion control and maintenance (see Appendix A7 for details).

5.5.1 Reinforcing measures

In general, intensive green roofs are applied on slopes of up to 5°, while extensive green roofs on slopes of up to 30°. The maximum slope that is commonly used for extensive green roofs is 45°. As the steepness of the slope increases, the structure requires more protection against shear and slide forces and controlled drainage and soil depth should be considered.

Generally, green roofs should not be applied to roofs with slopes greater than 45° due to the extreme difficulty in managing soil moisture on a roof of such steepness. In such slopes the water will tend to run out of the system, resulting in dry areas at the top and moist areas at the bottom. For slopes of angles less than or equal to 20° (36% gradient), anti-shear protection is not required, but it is needed for slopes at angles greater than 20° (36% gradient). In cases where angles are greater than 30° (58% gradient), separate static calculations are required to ensure that the action taken to prevent shearing doesn't create tension at the contact point with the waterproof membrane and the root barrier. A summary of the reinforcing measures with increasing slopes is shown here:

- 10–15°: use root resistant waterproofing/reinforced eaves.
- 15–20°: use anti-erosion net.
- 20–30°: use additional shear barriers.
- >30°: use pre-cultivated elements or vegetation mats.

5.5.2 Design considerations

To protect plants from erosion or sliding, the support course of the plants should be cultivated in a way that ensures that the structural soundness is not affected by water. This can be achieved by using fine- to medium-sized chipped gravel or by minimising the amount of material that could get washed out.

On a roof slope greater than 20°, the green roof installer needs to ensure that the sod or plant layer does not slip or slump through its own weight, especially when it becomes wet. This can be prevented by using horizontal strapping, wood, plastic or metal placed under the membrane or loose-laid on top. Support grid systems for green roofs have been designed by some green roof suppliers specifically for this application.

Whether a roof is green or not, a slope of 1–2% should be applied on it to allow water to move smoothly towards the drain holes (openings). This slope is usually maintained using a lightweight concrete (screed) layer between 50–70 mm thicknesses. Appendix A7 provides more detailed information about design considerations for pitched green roofs.

5.6 Sustainable technologies

Green roof systems can incorporate other sustainable technologies to improve the environmental performance and energy balances of the building. For example, the integration of green roofs and renewable energy systems such as solar photovoltaic (PV) and wind energy can lead to a better use of roof space and higher efficiency of the solar systems. The power generated from the solar PV or wind energy systems can be used to provide power supply on the roof (e.g. for lights for access, emergency exit signs and water pumps). Green roofs retain a high amount of rainwater so are perfect for harvesting and recycling rainwater, which drastically reduces the amount reaching the urban sewage system. The excess rainwater is of good quality and can be used in flushing toilet systems or for irrigation purposes. It is also possible to attain clear runoff water if special substrates are being used for achieving the filtration.

5.6.1 Integrated design concepts

To illustrate how green roofs can integrate with sustainable technologies, a pilot study set up in a primary school in Hong Kong in 2008 is described here. Figure 5.6 describes the concept of the integration and Figure 5.7 shows an overview of the roof area (which is on top of an assembly hall). The following sustainable technologies were applied in the study:

- irrigation water from rainwater harvesting
- electricity from micro-wind turbines (for water pumps) and photovoltaics (for a weather station)
- fertiliser from composting (installed on the ground floor).

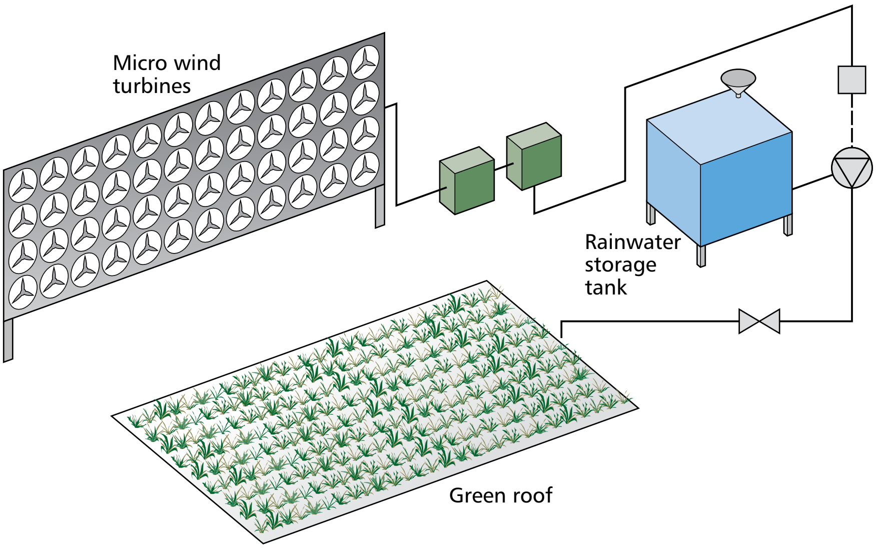


Figure 5.6 Integration of wind energy, rainwater recycling and green roof system

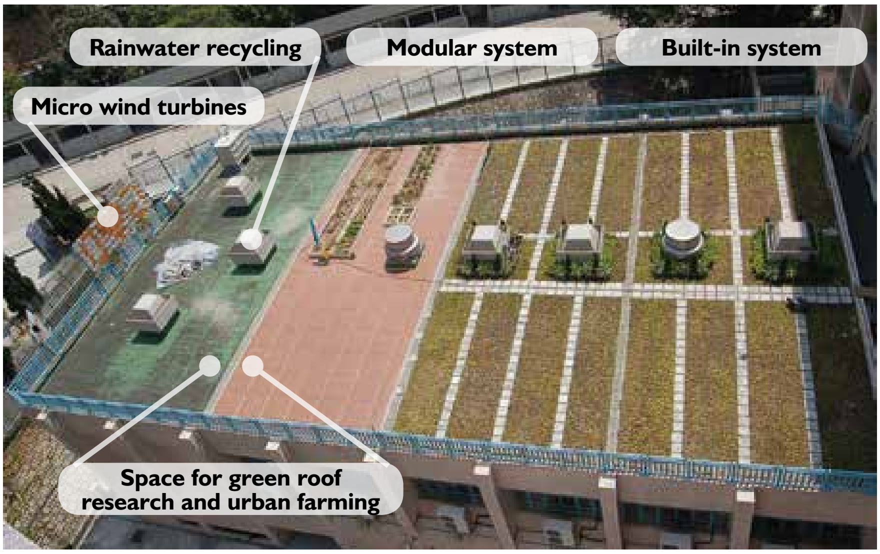


Figure 5.7 Integrated green roof systems at the assembly hall of a primary school

5.6.2 Green roof and solar photovoltaic systems

A new and quite successful trend is to integrate solar PV panels on green roofs (Hui and Chan, 2011). Studies have shown that there is a symbiotic beneficial relationship between green roofs and solar panels through creating an interesting microclimate. The green roof lowers the roof's temperature and ensures greater solar-panel efficiency. In turn, the solar panels shade the roof from excessive sun exposure and high evaporation, thus providing temporary relief from the sun, reducing drought stress of plants and allowing for a wider range of planting choices from full sun to half shade. Figure 5.8 shows an example of green roof and solar PV integration. The main advantages of this combination are easy installation of solar unit, reliable stability of solar units from the load of the green roof build-up and higher efficiency of the PV module due to the cooling effect of the green roof.

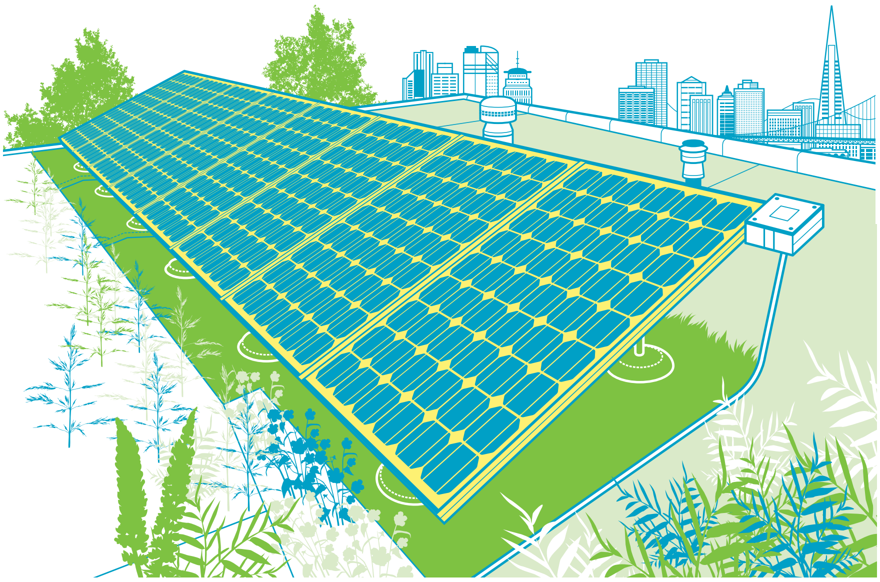


Figure 5.8 Example of green roof and solar PV integration (Peck and van der Linde, 2010)
Credit: Jameson Simpson

On roofs with solar panels, usually only extensive vegetation can be installed. The solar units have to be installed above the vegetation level so that the panels are not shaded. Special frames of aluminium are made in order to put the panels above the vegetation level. In traditional solar PV systems, the solar units were mounted on concrete bases or slabs and partially filled with gravel; however, they are now mounted on a framework that is fixed to plastic boards. The profiled plastic boards are covered with substrate and allow rainwater to drain through, thus, allowing plants to grow underneath the solar panels. With the solar panels mounted on the plastic boards, the load distribution is spread over a large area and prevents the roof construction from being damaged by point loads. However, if such detail is too complicated for a green roof project, solar PV and green roofs can be put side by side. Figure 5.9 shows one example of such design in a library building in Taiwan (and can be compared with Figure 5.8).

Figure 5.9 Green roof and solar PV systems at the Beitou Taipei Library, Taiwan

5.6.3 Sustainable materials

If the green roof components are made from recycled or waste materials (such as crushed clay brick or tiles, or brick rubble) and obtained from local or regional sources, this could contribute to reducing the environmental impacts on the material side. To be more sustainable, materials should be environmentally friendly in terms of the amount of energy consumed to produce the material. Locally sourced materials are better than importing expensive ones. Endemic and indigenous plant species are recommended, with plant schemes emulating the communities found in the local environment.

5.7 Farming and food production

Green roofs can also have various uses if the structural engineering and the accident prevention measures allow. The roofs can be used for growing crops, recreational gardens, roof cafes or leisure and sporting facilities. Accessible roof gardens can be designed as rooftop allotment gardens for local food production or beehives used for honey. The produce can be used by the farmers or supplied to kitchens/restaurants and markets. By setting up edible rooftop gardens or farming on suitable buildings, it is possible to promote more useful and meaningful functions for green roofs (Hui, 2011).

5.7.1 Agricultural green roofs

In recent years, concerns about the environment, combined with increased interest in health and community-building issues, have increased support for food systems as an integral part of sustainable development. Figure 5.10 shows how green roofs could contribute to the sustainability of an urban environment, by promoting and integrating green building, urban greenery and urban agriculture.

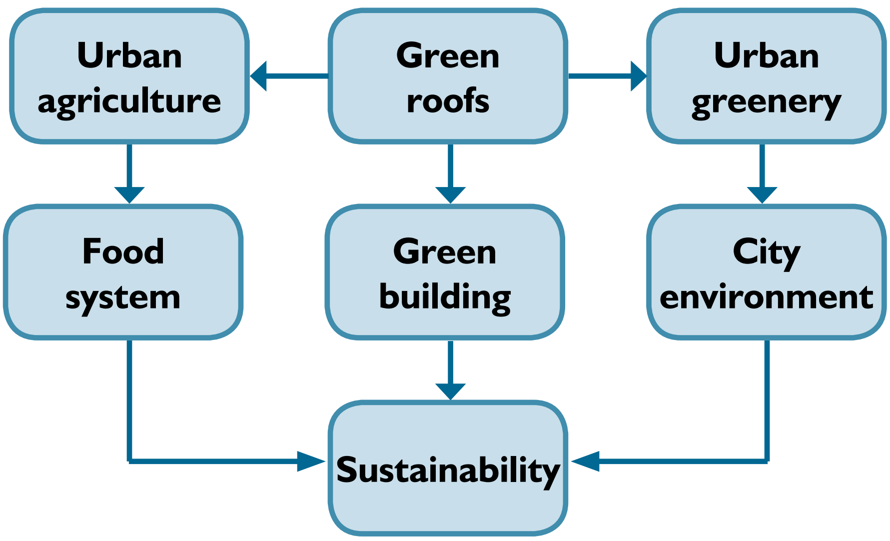


Figure 5.10 Contribution of green roofs to sustainability of an urban environment

Rooftop farming has other benefits and has different design requirements and implementation considerations to non-agricultural green roofs. Agricultural green roofs enhance sustainability in the urban city by:

- producing food (e.g. community gardens and growing healthy food)
- providing active recreation
- re-using waste (compost, rainwater)
- providing educational opportunities
- creating local jobs (direct and indirect).

Figure 5.11 shows some pictures of a pilot study on sustainable rooftop farming in a primary school in Hong Kong (see also Figures 5.6 and 5.7). Organic farming, on-site composting for producing fertiliser, rainwater harvesting and renewable energy (micro-wind turbines and solar PV system) are used. The farming is carried out by the students and their parents, with the support from the schoolteachers. The vegetables and produce are shared by the students.

Figure 5.11 Pilot study on urban farming for green roofs

5.7.2 Design strategy

Although green rooftop farming has a lot of benefits, there are a few constraints and limitations on farming in urban areas:

- lack of available land and suitable space
- land use control and building regulations
- microclimate conditions
- the urban way of living makes people disconnect with their own communities.

Green roofs might not replace large-scale farms, but they can help develop a model for small-scale food production. Community gardens on rooftops can be places for education and local distribution, as well as a showcase for commercial endeavours such as restaurants using the roof for kitchen gardens. Figure 5.12 shows examples of rooftop urban farming in other countries. For example, a proposal to develop rooftop farming in the public housing estates in Singapore was put forward to address the issue of food security and reduce the carbon footprint associated with food imports (Lim and Kishnani, 2010). If such a scheme is implemented extensively in Singapore, it could result in a 700% increase in domestic vegetable production, satisfying domestic demand by 35.5%.

Green roofs for food production require little alteration from the standardised system, but a few issues need to be considered.

- The depth of the growing medium needs to be sufficient for anchoring and sustaining food plants.
- Waterproofing membrane needs to be sufficiently protected from frequent use of gardening tools.
- Fertilisation may be required to sustain nutrient availability in heavily used growing medium.
- Safety and quality of produce must be considered.

Figure 5.12 Examples of rooftop urban farming
Left: Brooklyn Grange Farm, New York City
Credit: Cyrus Dowlatshahi
Right: Rooftop container garden in Taipei, Taiwan
Credit: Patrick Cowsill: www. patrick-cowsill.blogspot.co.uk

5.8 Implications for building services design

Green roof systems are relatively new to building services engineers. It is important to understand the major implications of rooftop greening when designing the building services systems so that the building's performance can be enhanced and the benefits of green roofs can be achieved.

5.8.1 Integration with green building design

As mentioned in Section 4.5, green roofs can often be a useful design feature for obtaining green building credits in green building assessments. When planning the building project, it is essential to consider the potential and extent of greening to ensure the building structure and engineering services systems are designed to support the green roof systems. The proposed location and size of the green roofs should be identified and the building services requirements (such as water supply and drainage, electricity and lighting) and space limitation should be considered.

Green roofs can be designed in conjunction with other green features, such as solar panels and rainwater harvesting systems. They also work well in combination with other low-impact development measures, such as infiltration beds, rain gardens, bio-retention systems, cisterns and rain barrels. For instance, large developments that have zero runoff discharge are common in Germany and Switzerland. In these developments, rainfall is captured on the vegetative roofs, returned to ground water through infiltration and reused for irrigation, toilet flushing, etc.

5.8.2 Coordination with other rooftop services

Green roofs are well suited to commercial buildings where there will often be an air conditioning plant, water storage tanks, lift machine rooms, gondola lifts, etc. on the roof (Hassell and Coombes, 2007). Attention needs to be paid to detailing around the mechanical plant and to access

Figure 5.13 Green roof design coordinated with a gondola lift in a commercial building in London

across the green roof. Figure 5.13 shows an example of green roof design coordinated with a gondola lift in a commercial building in London. The roof space at the perimeter is used for the gondola track; the interior is designed as a roof garden and landscape for people to carry out amenity functions. As access is required for the mechanical plant, access for maintaining the green roof is simplified.

Because of the importance of waterproof membrane integrity, rooftop services piping, ducts and wiring should never pass through the membrane. If they must be placed on the roof they should be connected via the parapet, which should bear the load. This can prevent water leakage problems with the membrane.

Some buildings use green roofs try to avoid rooftop services. For example, the green roof may be placed at a mezzanine level with services concentrated on the main tower. In some other buildings, the building services are placed in the void floor immediately below the roof. This design strategy can separate the green roofs from other rooftop services to avoid conflicts.

5.8.3 Water drainage and storage

Green roofs must achieve a balance between adequate drainage and storing water to prevent it drying out, which requires appropriate drainage products and growing medium. However, the selection of a specific plant community, greater plant diversity, or simply the particular design parameters desired for certain green roofs may require additional water.

As stated in Sections 3.1 and 5.2, some drainage layers also incorporate water-retention capabilities; the stored water reaches the plants by capillary action. An optional reservoir board layer or retention mat can be installed to retain and store small amounts of water. A simple automatic drip irrigation system with a manifold delivering water at the base of the profile can also be installed or a more complete (and heavy and costly) irrigation system can be incorporated into any intensive green roof design that can withstand the added weight.

Water pressure required by the green roof at its level is unlikely to be adequate for suppressing vegetation fires. While initial planting plans may suggest arid operation, the option should remain open for future irrigation models. In general, most green roofs buffer short periods of high rainfall but once saturated perform hydraulically as a conventional roof. Drainage design therefore remains the same as for a conventional peak runoff. It may be necessary to make special trap provision to remove silt.

5.8.4 Stormwater management and rainwater recycling

When a green roof is installed on the building, the sizing of rainwater downpipes might be affected (Hassell and Coombes, 2007). A green roof results in a reduction in total runoff volume and also a reduction in peak flow. The reduction in peak flow depends on the intensity of the rainfall and the level of saturation of the substrate beforehand. When the substrate is saturated the lag time can shorten to that from a hard roof, but peak-flow reduction can still occur.

Clients committed to green roof philosophy are likely to be attracted to collection of rainwater as a greywater supply. The water collected, while above the standard of conventional greywater, is unlikely to meet drinking water standards unless processed (e.g. by using carbon filter). Rainwater runoff from a green roof is less than that from alternative roof designs and the runoff will carry fine sediment held in suspension. However, rainwater can be collected from a green roof and used either to water the roof itself or around the building to water other vegetation. If fertilisers are used on the roof then the runoff should not be used to keep ponds topped up, as high nutrient levels lead to uncontrolled algae growth. Using rainwater collected from a green roof back in a building is not recommended because the water will be discoloured.

5.8.5 Thermal properties and energy performance

Green roofs insulate buildings by preventing heat from transmitting through the building roof. The reduction of heat gain from the roof will reduce the cooling energy consumption of air conditioning system. Research has shown that green roofs will reduce the amount of cooling required in a building significantly (Hui, 2006). A green roof will not absorb as much solar energy as a conventional flat roof and so the roof structure will heat up much less. At the same time, evapotranspiration from the vegetation will dissipate heat that is absorbed and the substrate itself will act as an insulating barrier.

The insulation properties can be maximised by using a growing medium with a low soil density and high moisture content. The benefit of solar heat gain reduction will be realised most fully in warm climates, where energy expenditures on air conditioning are high. However, this benefit will be less significant in multi-storey buildings because of the low ratio of roof area to the total exposed building facade. Since green roofs are more complex than simple insulators, project-specific building envelope analysis is required to predict energy effectiveness under specific project conditions.

Some research has shown that a green roof can also slightly reduce heating demand, but the amount of heat loss mainly depends on roof insulation thickness (Hassell and Coombes, 2007). Potential savings in heating demand achieved by a green roof depend on varying factors, such as location, amount of growth, whether watered or not and amount of water held in the substrate, and will vary throughout the heating season on a daily basis. For example, the research studies in Toronto (Liu, 2003) and Berlin (Köhler, *et al*., 2001) indicated a summer energy saving of 4.15 kW·h/m^2 and a winter saving of about 2–6 kW·h/m^2, respectively.

6 Construction methods

Contractors should be fully trained in the installation of green roofs and must have a specialist understanding of the green roof system as well as general construction knowledge. In general, green roof contractors should have knowledge and training in the following areas:

- site preparation prior to installation
- preparation and logistics
- essential system components
- growing medium
- planting programme
- installation of support system to the plants
- installation of plants
- post-installation maintenance.

6.1 Green roof installation

The installers should have experience with green roof systems. It may be preferable for one company to handle the whole project, from re-roofing to planting, thus avoiding scheduling conflicts and damage claims between the various trades. It will also bring single-point responsibility post-construction.

Some plants can be installed while dormant but during the rainy season there may be some erosion of the growing medium through wind and rainwater runoff. Covering the roof with burlap or another other material could reduce this problem. Compartmentalisation of the green roof into sections may allow for easier access to the membrane and the roof drains for inspection and maintenance, without having to pull up the whole installation.

Due to the diversity of products available from the various green roof suppliers, it is recommended that specific installation advice is sought from the system provider to ensure compliance with suppliers' recommendations.

Methods for getting the materials up to the roof should be discussed to determine cost and potential equipment rentals. Timing is also important. How substrate is lifted up to roof level and dispersed across the roof has significant budgetary and scheduling implications. Each project should be assessed for its specific conditions (i.e. roof area, slope, structure, access, plant equipment availability, etc.) to determine the most time- and cost-efficient installation method.

6.2 Safety issues

Working on roofs bears a higher risk for accidents due to the exposed location. This must be taken into consideration during the planning, design and installation phases. The need to have fall arrest systems is universal for green roof systems, however the type of system required varies depending

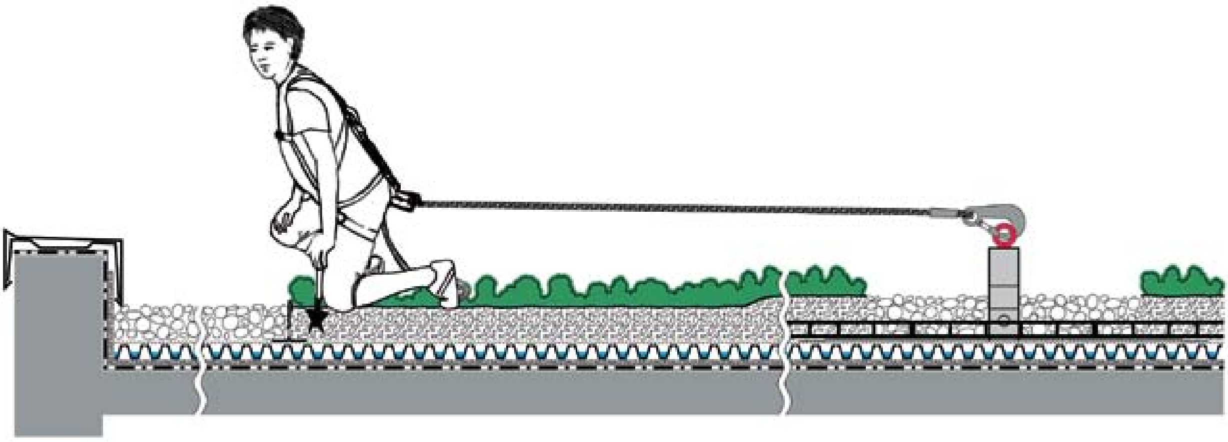


Figure 6.1 Safety measures to avoid falling from height
Credit: Zinco

on the type of green roof and the maintenance required. Securing measures are necessary at a height of more than 3 m. Fall protection measures include railings, scaffolding, nets, ropes and chains. Various systems provide fall protection by using the weight of the green roof system build-up and also avoiding the penetration of the waterproofing. Figure 6.1 shows the safety measures to avoid falling from height.

Strict safety standards and requirements for protection against falls have to be taken into account during planning, execution and utilisation of the roof (CUGE, 2010c). For example, railings for public access, anchors for maintenance access and barrier-free direct access path to that emergency exit should be provided. Roof access staircases must be non-slippery and equipped with handrails. Potential dangerous items such as TV cable and electric wire should be removed or relocated, if needed.

6.3 Fire precautions

Green roofs, like any vegetation-covered surface, need to be designed to provide the necessary resistance to the external spread of fire, even when subjected to prolonged periods of drought (SPRI, 2010b). There is evidence suggesting that green roofs can help slow the spread of fire to and from the building through the roof, particularly where the growing medium is saturated. However, plants can present a fire hazard if they are dry. The integration of 'fire breaks' at regular intervals across the roof, at the roof perimeter and around all roof penetrations is recommended. Certain plants should be avoided for fire safety reasons, such as plants that are highly flammable, develop large root systems and thus high biomass or are excessively thirsty.

Traditional 'biomass roofs' made of reeds may be a high fire risk. In general, fire risk of extensive green roofs is not high because the heat load of burning the drought-tolerant plants is low (burn-resistant) and flammable materials are not used for green roof components. In fact, in some buildings, extensive green roofs can be used to reduce the risk of fire. Intensive green roofs provide preventative fire protection in the case of sparks and radiating heat. The criteria that extensive green roofs must meet in order to be considered fire resistant are already met by most green roof systems that are offered by suppliers. Openings within the green roof (e.g. skylights) need to be installed with a vegetation-free zone (approximately 500 mm). On larger roof areas, a vegetation-free zone or fire stops (e.g. gravel strip or concrete slabs) should be installed at least every 40 m and around the parapet.

6.4 Vegetation planting method

There are four different ways of planting the green roof vegetation:

1. seed sowing
2. cuttings (sedum varieties)
3. root ball plants
4. pre-cultivated vegetation mats.

The German FLL guidelines (FLL, 2008) specify the amount of seeds, cuttings, plants or mats needed for green roofs. The recommended planting period is in early spring (April–June) and late summer (September). For planting during the dry season, it is important to provide enough water to compensate for periods of low precipitation. In winter, precautions should be taken to prevent damage of the plants due to cold weather. Pre-cultivated plants should be stress resistant to avoid higher irrigation and fertilisation maintenance. Table 6.1 shows four different planting options for extensive green roofs.

Table 6.1 Planting options for extensive green roofs

Planting options	Description
Mono-culture planting	This type of planting is simple and usually uses only one plant species. It is the easiest to plan and install. It is argued that mono-culture plantings are visually uninteresting, but sometimes a uniform appearance may be appropriate. From an ecological viewpoint they may be susceptible to total die-back if drought or disease severely affects the species in question.
Pattern planting	This type of planting is used primarily for its visual effect but uses more than one species. A wide range of designs are possible; design elements that affect the design include: materials and colours; proportion and balance; texture, pattern and line; rhythm and repetition. This approach may require higher maintenance than other planting approaches.
Mixed planting	The approach uses a mix of species to create a random but colourful carpet. It is a relatively safe approach, as the various species will eventually find their own equilibrium. This approach does not necessarily use indigenous species and in most parts of the world uses a mix of sedums.
Plant communities planting	This approach is based on natural habitats. Plants are chosen and combined in proportions approximating nature and their occurrence in the wild. Community-based planting tends to be self-sustaining, requiring low maintenance. Green roofs that use this approach usually look informal and natural; the use of wild grasses can be considered untidy. Some examples from overseas have careful and diverse selections of plants that flower almost year round. This approach strives to use indigenous plants to fulfil a green roof's maximum ecological potential.

Adapted from: Dunnett N and Kingsbury N (2008) *Planting Green Roofs and Living Walls* (revised and updated edition) (Oregon: Timber Press).

The vegetation layer can be installed using the following methods.

Sedum mat

A carpet of sedum species is field-grown to maturity, enabling it to be rolled directly onto the prepared substrate. The installed sedum mats should be thoroughly watered in and kept moist for four to five weeks until the sedum mats become established. Mat edges are typically butt-jointed, although the specific supplier should be consulted to establish any shrinkage risk.

Plug planting

Rooted young plants (plugs), typically sedum species, are individually grown (in trays) and planted, giving the opportunity to provide a greater diversity of planted species. Subject to the plant species selected, plants should be installed at a typical coverage rate of 15–20 plants per m^2. A minimum of six varieties of species per m^2 is recommended.

Before the planting, the substrate, drainage layer and any moisture mat should be saturated. The plants should be watered before removing them from their trays. An approved slow-release fertiliser can be applied onto the substrate (at an approximate rate of 50 g per m^2). The plants should be inserted and gently watered. The substrate should be kept moist for an initial period of four to five weeks to allow the plants to sufficiently establish themselves.

Hydroplanting and seeding

A mixture of sedum cuttings and seeds are spread on the prepared substrate, with mulch applied to allow cuttings to root and seeds to germinate. A minimum of six sedum species should be represented in the mix of cuttings and seeds, applied at a rate of approximately 150 g per m^2 onto the surface of the substrate. The plant mix is typically spread by hand and covered with a liquid-applied mulch and an appropriate organic nutrient source.

6.5 Plants and growing medium

The plants will require most attention during the critical establishment phase, which lasts approximately 18–24 months (unless the green roof is pre-grown and close to being established upon installation, as in the case of some modular systems). New green roofs will succeed, with proper plant selection and care. A horticultural professional can help people who are caring for the green roof to organise schedules and routines for the following essential garden tasks.

- Hand weeding: throughout life of the roof.
- Watering: especially during the establishment phase and possibly throughout the life of the roof and/or during droughts.
- Thinning: after the establishment phase to promote plant health.
- Pruning: after the establishment phase to promote plant health.
- Fertilising: may be used during the establishment phase to promote plant health (organic products are recommended). Fertilisation

should be done thoughtfully, keeping in mind that green roofs are confined planting areas. Excess fertiliser will be carried in rainwater runoff and is likely to end up in waterways.

- Replacing planting and in-fill in areas where plants have died off might be necessary for adequate surface coverage.

Not to be confused with soil, the growing medium is distinguished by its mineral content, which is often synthetically produced, providing the basis for an ultra lightweight growing medium. Applying the wrong type of growing medium can result in inadequate drainage (leading to collapse), excessive weeds (seeds in the substrate), loss of species diversity and loss of organic content through mineralisation. The thermal mass of the growing medium plays a significant role in dampening the impact of ambient temperature fluctuations. This property can dramatically affect heat transfer through roof systems in hot climates.

In general, intensive green roofs need more organic matter to retain water and provide nutrients; extensive green roofs need more mineral aggregates to retain water. The composition of growing medium is determined by weight loads, climatic conditions, drainage needs and plant requirements. Growing medium should be applied damp, with plants covered until they are established, to stop it being blown away.

Water retention is another important parameter that can vary with the type and amount of vegetation, growing medium composition and climate. Since absorption and flow rates are site and system specific, estimates of water retention characteristics must be calculated for individual cases. Growing-medium depth and composition must also be appropriate for the selected vegetation.

Watering and weeding is especially important during the first two years of the green roof. The roof requires careful weeding before weed seeds are produced. Sterile growing media may also contain weed seeds. A certain amount of weed growth is inevitable, as seeds arrive on the roof via wind, birds and shoes. For overall health of the green roof, weeds should be identified and removed early and often.

6.6 Inspection and testing

Vertical components rising from the main structure, such as walls, vents, heating, ventilating and air conditioning (HVAC) systems and electrical boxes should not generate pressure on any part of the roof membrane, which could potentially compromise the membrane and cause water ponding or leaks. Regular inspections should take place around these vertical components to keep them clear of debris. These inspections may be scheduled at the same time as drain inspections.

Remedial works to the waterproofing require extensive investigations simply to locate the point of fault. Combined with the fact that the removal (and subsequent replacement) of the green roof build-up is so labour intensive, significant costs can arise from problems with the waterproofing layer. The inspection and testing of the water integrity of the roof covering before installation is therefore imperative, especially for existing buildings (Liu, 2011).

A 'walk through' is usually conducted with the roofing consultant and the general contractor before installing the membrane. It is imperative that the deck surface is prepared properly before installing the membrane. After membrane installation and before installation of all additional green roof system layers, a membrane leak detection test should be conducted to ensure the waterproofing membrane doesn't have any leaks. The membrane test can help pinpoint design and construction errors and helps maximise owners' protection under the terms of the roof contract and roof warranties. This test ensures that the roof has no leaks and is free from hidden defects in both waterproofing and flashing systems. Automatic leak detection systems that can notify the owner of leaks after the green roof has been installed are also available.

The types of tests usually used for leak detection are flood test and flowing test. Other strategies for detecting leaks include electric field vector mapping, capacitance (impedance) testing, infrared thermal imaging and moisture sensors. Table 6.2 shows the testing methods for leak detection.

Table 6.2 Testing methods for leak detection

Method	Description
Flood testing	A procedure in which a controlled amount of water, usually 10 cm, is temporarily retained (i.e. drains are closed, or sloped areas are dammed) for a period of 24–48 hours over a horizontal surface to determine the effectiveness of the waterproofing system.
Flowing test	Water is flowed continuously over the surface of the waterproofing membrane for a minimum of 24 hours without closing the drains or erecting dams.
Electric field vector mapping (EFVM)	A conductor wire is looped around the area to be tested, on top of the membrane and connected to an impulse generator before other components are installed. During testing, an electric current is delivered at short, regular intervals. The current flows across the membrane, to any breaches, where it can access the grounded structural deck. Using a receiver connected to two probes, the testing agent can identify the current's flow and accurately locate the breach.
Capacitance (impedance) testing	This utilises an electric field to determine the relative moisture content on and below the membrane, but may not pinpoint the exact leak. For accuracy during testing, the membrane must be dry and the assembly should be a uniform thickness and material.
Infrared (IR) thermal imaging	An interpretive testing method based on the principle that wet and dry building components have differing rates of heat gain and retention. It can cover large areas quickly and cost effectively above and below the surface of the membrane but may not pinpoint the exact leak. This testing method is not useful after a green roof has been installed, since the green roof reduces heat reflection.
Moisture sensors	Moisture sensors at suitable locations on the green roof detect possible leaks.

Before installing the above-membrane components (drainage panel, growing medium, vegetation, etc.), the contractor will conduct a standing water leak test (also known as a flood test). The test will involve flooding the entire green roof area with at least 50 mm of standing water for a period of at least 24 hours with drains and scuppers blocked. Before draining the standing water, the owner's representative, supplier's representative and contractor will inspect the roof for leaks from below and from the roof surface; this will include walking all membrane seams. Once the standing water has been drained, the roof will be inspected and all membrane seams walked again. If areas are suspected to be leaking, the contractor will perform test cuts according to the supplier's directions. If the test cuts are wet, the contractor will patch the test cut as per the supplier's specifications and the flood test will be repeated.

In addition to leak detection, checking that the slope is adequate for drainage is also important. A maintenance plan should be established before a green roof is completed. Plant maintenance and membrane flashing points/roof structural elements inspection are regularly required.

7 Maintenance issues

All roofs—green or conventional—require regular maintenance, which can determine the success of green roof systems (Urbis Limited, 2007). The maintenance requirements of green roofs are determined by many factors—height, microclimate, soil types, soil depth, irrigation, species and access. In high-density cities like Hong Kong, access is often a crucial factor influencing maintenance costs. Green roof design should take this into consideration.

Maintenance conducted by qualified personnel will ensure the successful initial establishment and continued health of the green roof system. It is recommended that the installing contractor remains responsible for maintaining the green roof during this establishment stage (12–15 months) before handing over maintenance duties to the building owner's representative. Maintenance contractors with specialist training in green roof care should be used, where possible.

7.1 Three stages of maintenance

To ensure the long-term aesthetic and functionality of the green roof, it is important to provide maintenance measures in a systematic way. There are three stages of maintenance concerning the vegetation.

1. Installation maintenance: several aspects of maintenance and service are needed throughout the first year. It is important to provide a sufficient water supply during the dry season. Replanting is necessary if there are dying or missing plants after installation and weeds and other unwanted plants need to be removed.
2. Development maintenance: it is essential to support the vegetation until total coverage of the roof is achieved. The development maintenance is a lower-intensity equivalent of the installation maintenance.
3. Upkeep or ongoing maintenance: after the plants on the green roof have developed, it is crucial to maintain and inspect the roof once or twice a year. Weeds and other unwanted plants on the entire roof, at the perimeters and at the upstands need to be removed. The irrigation system and inspection chambers need to be monitored to ensure that water outlets are free from blockages. For grass and herb vegetation, the organic material has to be removed once a year and grass needs to be pruned regularly. Intensive green roofs require higher maintenance and service throughout the year.

7.2 Maintenance requirements

Green roof plants require regular attention and care including irrigation, weeding, fertilising, pruning and replanting. Some maintenance procedures should be scheduled after events (such as floods and storms) while others can be scheduled according to seasonal events. Like any garden, roof gardens require frequent maintenance. However, extensive green roofs do not require any more maintenance than a conventional roof. They should be inspected annually in order to remove any unwanted plants and to unblock drains. Other types of green roofs will require more frequent maintenance, particularly if food is being produced. Appendix A8 gives a checklist for green roof maintenance.

7.2.1 Plant and waterproofing membrane

Both plant and waterproofing membrane maintenance are required. Depending on whether the green roof is extensive or intensive, required plant maintenance will range from two or three inspections every year to check for weeds or damage, to weekly visits for irrigation, pruning and replanting. To ensure continuity in the warranty and upkeep, the fees for three to five years of this service should be included in the original bid price, and maintenance contracts are awarded to the company that installed the green roof or an affiliate. Intensive systems typically require more maintenance than extensive systems due to the greater diversity of plants.

Maintenance and visual inspections of the waterproofing membrane can be complicated by the fact that green roof systems completely cover the membrane. Although the green roof protects the membrane from puncture damage and solar radiation, doubling its lifespan, leaks can occur at joints, penetrations and flashings, usually due to sloppy installation not material failure. Regular maintenance inspections should be scheduled as for a standard roof installation, especially just before the warranty period ends.

7.2.2 Leak detection and membrane replacement

Some companies recommend incorporating an electronic leak detection system between or underneath the waterproofing membrane to pinpoint the exact location of water leaks (see also Section 6.5). Access strategies include keeping the sensitive areas free of plants and growing medium (e.g. gravel skirts) and dividing the green roof into distinct compartments for ease of removal.

Eventually, after 30–50 years, the membrane will have to be replaced. Depending on the roof size, building height, type of planting and depth of growing medium, the system will either be removed and reinstalled over the new membrane or replaced entirely. If the green roof can be removed and stored on the roof while the membrane is being replaced in sections, the additional cost is ‘labour only’ over the original cost. If it has to be moved off the roof and brought back up, costs will increase accordingly, so the arguments for starting afresh, with new growing medium and plants, become more convincing.

7.3 Design for maintenance

At the design phase, it is important that any budgetary constraints are accounted for. The costs of roof maintenance should form part of the lifecycle cost analysis for the building, allowing the most appropriate green roof specification to be realised.

7.3.1 Major considerations

As a minimum, the following should be considered during design development to ensure ease of maintenance for green roofs during and after installation.

- Access for equipment and inspections following construction.
- Access for water is very important in most green roofs. Irrigation system, growing medium and plant selection are critical factors determining long-term maintenance requirements and survival of the green roof vegetation under hot, dry conditions; otherwise, vegetation may have to be repeatedly replanted and/or the irrigation system replaced. Access to multi-functional irrigation timers is recommended.
- If an under-drain system is used, provide a clean-out for both inspection and maintenance. There is potential for it to become clogged with growing medium and organic matter that migrates down beneath the plant root zone. The ability to access the under-drain system, flashings, drains, etc. for clean-out is essential.

Plants are susceptible to insufficient drainage in the soil. If too much water is present and unable to drain, the plants will drown or rot. Regular inspections of drains should take place approximately three times per year, with additional inspections advised after major weather events. All drains must remain free of vegetation and foreign objects. Inspecting drainage flow paths is crucial because of the severe consequences of drainage back-ups. In order to allow for regular inspections and maintenance, every drain on a green roof must remain permanently accessible. Roof outlets, drains, interior gutters and emergency overflows should be kept free from obstruction by either providing a drainage barrier (e.g. a gravel barrier between the green roof and the emergency overflows) or they should be equipped with an inspection shaft.

With proper design and regular maintenance, green roofs should last over 40 years. If there is space and loading capacity, the green roof can be moved onto other areas of the roof and then returned to the original site, when waterproofing is replaced. Some extensive systems can be removed intact and relocated.

7.3.2 Maintenance procedures

The waterproofing roof membrane is the most vital aspect of green roof longevity and success. There are areas where inspections are advised at least three times per year. These include all joints, borders or other features penetrating the roof, such as all abutting vertical walls, roof vent pipes, outlets, air conditioning units and perimeter areas. Joints must offer open access for inspection, maintenance and upkeep. Any areas or joints where the roof is penetrated (such as vents, ducts, drains and expansion joints, etc.) should be regularly inspected and kept free of roots, leaves, rocks and debris. A vegetation-free zone 300–500 mm around the perimeter of the roof and around all drainage locations is recommended. The vegetation-free zone typically has rocks, stone or gravel.

Although the green roof system is built for low maintenance, extensive green roofs still need to be maintained to ensure healthy growth of plants, proper functioning of drainage layer, etc. (DSD, 2009). Maintenance to ensure that unwanted plant species and weeding do not invade the green roof system by causing damage and dominating the original plantings is also needed. Undesirable plant species are best avoided by establishing complete coverage with the desired plant species. Any wind-blown seeds or cuttings should be removed before they have the opportunity to take root. Drainage outlets (including inspection chambers) and shingle/gravel perimeters should be cleared of vegetation twice a year. It is also important to investigate how to keep birds from inhabiting. Table 7.1 shows the green roof maintenance procedures suggested for Hong Kong.

Table 7.1 Maintenance procedures for green roofs (Urbis Limited, 2007)

Maintenance procedure	Intensive: podium or sky gardens	Extensive: extensive green roofs on existing roofs	Notes
Waterproofing inspection	Once a year	Once a year	Inspect for water penetration through the concrete.
Drainage inspection	Once a month	Every two months	Inspect drainage outlets.
Litter	Once a week	None/as necessary	Includes removing litter and emptying bins, depends largely on the type of green roof, visitor numbers and occasional litter that may fall on it.
Plant health inspections	Six times a year	Twice a year	Check for insect and fungus infestations (particularly relevant during establishment period).
Replacement planting	As necessary	As necessary	
Irrigation	780 l/m^2 per year	Low to none	Based on 15 l per week (reduced from 25 l due to Hong Kong's high rainfall during summer) amenity planting.
Pruning	Twice a year	N/A	
Lawn mowing and rough grass cutting	Nine times a year Up to three times a year	N/A Up to three times a year	Depends largely on design and turf grass species. Fallow grasses require less cutting than turf grass.
Fertilising	Once or twice a year	Every four to five years	May be increased for horticultural practices that remove biomass from the system, such as lawn mowing.
Disease and pest control	Four times a year	Four times a year	Regular inspections needed.
Weeding	Nine times a year	Up to three times a year	Weeding for extensive green roofs should hardly be needed if installed it is correctly, self-seeded trees may be a problem in urban fringe areas.

7.4 Warranties and liability

Before implementing a green roof project, it is essential to understand project-specific needs for insurance and liabilities. Often these are tied directly to design, implementation, access and general use after project completion. Different green roof systems come with different warranties; drafting a plan during the design phase of a project in case of a future leak is recommended. This plan might include a strategy for surveying and potentially replacing the part of, or the entire, membrane. It might be helpful to plan a phased implementation, so only part of the roof would have to be exposed in order to survey and potentially replace part of the membrane in the event of leakage.

Not every warranty package is the same. A planted roof is a complete system and the waterproofing warranty should include all components of the waterproofing and planted roof. However, few suppliers will give a warranty on something they do not sell and, because green roofs are layered systems, this can sometimes be a challenge. Typically, a well-coordinated roofing consultant/roofing contractor and landscape architect/landscape contractor can help. A mediocre green roof system can be selected simply because the team/owner feels more secure with a full warranty from a single-source supplier (single-source suppliers count on this). It is vital that the warranties offered by the suppliers are carefully compared; some might seem inclusive at first but can be restrictive.

Building insurance should not increase with the addition of a green roof, unless it is made accessible for tenant or public use. All manufacturers of green roof products will provide a warranty for their products as long as they are installed as per their specifications. This sense of security can be a selling feature for some clients, especially institutions, even though the price is typically higher than combining individual 'off-the-shelf' products, which perform the same function but were not specifically designed for use in green roof applications. If cost is a concern, the only warranty or guarantee available for combining products will probably be related to the installation itself, and not the performance of the products.

If the entire system (waterproofing assembly as well as vegetated roof cover, including vegetation and growing medium) is provided by a single source, it is important to ensure the supplier's warranty includes the initial vegetation viability. In addition to the standard waterproofing warranty, the warranty should state that the proposed vegetated roof cover is completely compatible with the waterproofing assembly. The warranty for the vegetated roof cover should indicate that the proposed waterproofing system is compatible with the vegetated system (including plant climate zone, roof slope, and irrigation and maintenance requirements). If the waterproofing and vegetated roof cover are not provided by a single source, the waterproofing assembly should have a separate warranty so it is independent from any warranty for the vegetated roof cover.

7.5 Irrigation

Irrigation is typically required for the initial establishment of the green roof. However, once plant cover is achieved, irrigation can be reduced (for intensive and semi-intensive roofs) or avoided (for most extensive roofs, subject to plant selection). When planning green roofs, to save resources it is a good idea to select systems that will require no artificial irrigation. The more intensive the roof, the more likely it will be that an artificial irrigation system is required. Rainfall is the typical source of water, however complementary irrigation options include hoses, sprinklers, overhead irrigation and automated systems that pump from some reservoir storage.

Irrigation systems and plant water requirements are highly dependent on site location, water supply and pressure, maintenance access, size of planter, type of vegetation and the expected lifespan of plants and the irrigation system (Urbis Limited, 2007). Choice of principal irrigation methods depends on the cost, advantages and disadvantages of each system. There are three main ways of irrigating green roofs.

1. Manual hose irrigation: a 20 m hosepipe connected to water points located at 40 m spacing.
2. Fully automatic irrigation system: a programmed system that irrigates at set times, running continuously with minimal supervision.
3. Semi-automatic irrigation system: a programmed system with manual override options that are activated per day or as needed.

The irrigation should be designed for easy access and water efficiency. If possible, rainwater runoff should be collected and used for irrigation purposes. Water resources for green roof irrigation might include:

- roof drainage water (rainwater)
- recycled building greywater
- air conditioning condensate
- back-up water supply in case the water level inside the tank drops below the one-day irrigation requirement level.

The common types of irrigation method are: overhead spray, drip, hose bib or hose, and capillary. Figure 7.1 shows examples of irrigation methods.

The decision to use drip or spray irrigation is based on growing medium characteristics and plant needs. If the growing medium restricts lateral movement of water, drip irrigation might be insufficient. Custom detailing of irrigation systems may be necessary to avoid damage to the waterproofing membrane because of the shallow depths of growing medium. For example, typical concrete thrust blocks for irrigation mainlines may have to be detailed differently.

Drip irrigation can be more effective when installed below the vegetation layer to avoid the drip line heating and to improve root watering. Spray irrigation should be considered for shallow depth applications, as drip irrigation may not spread laterally when applied over a rapidly draining medium.

Research studies suggest that non-succulents dry out faster (need more frequent irrigation), whereas succulents require less frequent irrigation. However, succulents tend to die rather than go dormant during prolonged dry periods. Installing irrigation monitoring equipment such as timers, flow metres, sensors, runoff monitors and precipitation monitoring equipment can vastly improve irrigation procedures and conserve water.

7.6 Fertilisation

Fertilisation is the process by which additional nutrients can be supplied to the plants, enhancing germination, flowering and resistance to weather extremes. The regularity and type of fertilisation requirement depend on the type of green roof and its plant specification. Fertilisation is usually necessary during the initial establishment of the vegetation over the first and second growing seasons, after which occasional fertilisation (once or twice a year) might be necessary.

A correctly planted green roof will normally reach maturity in one or two growing seasons. The roofing contractor will know which chemical fertilisers and pesticides, if any, will not damage the waterproofing assembly or void the warranty.

Reducing or eliminating fertilisation of green roofs is recommended, as it can cause pollution in local water courses.

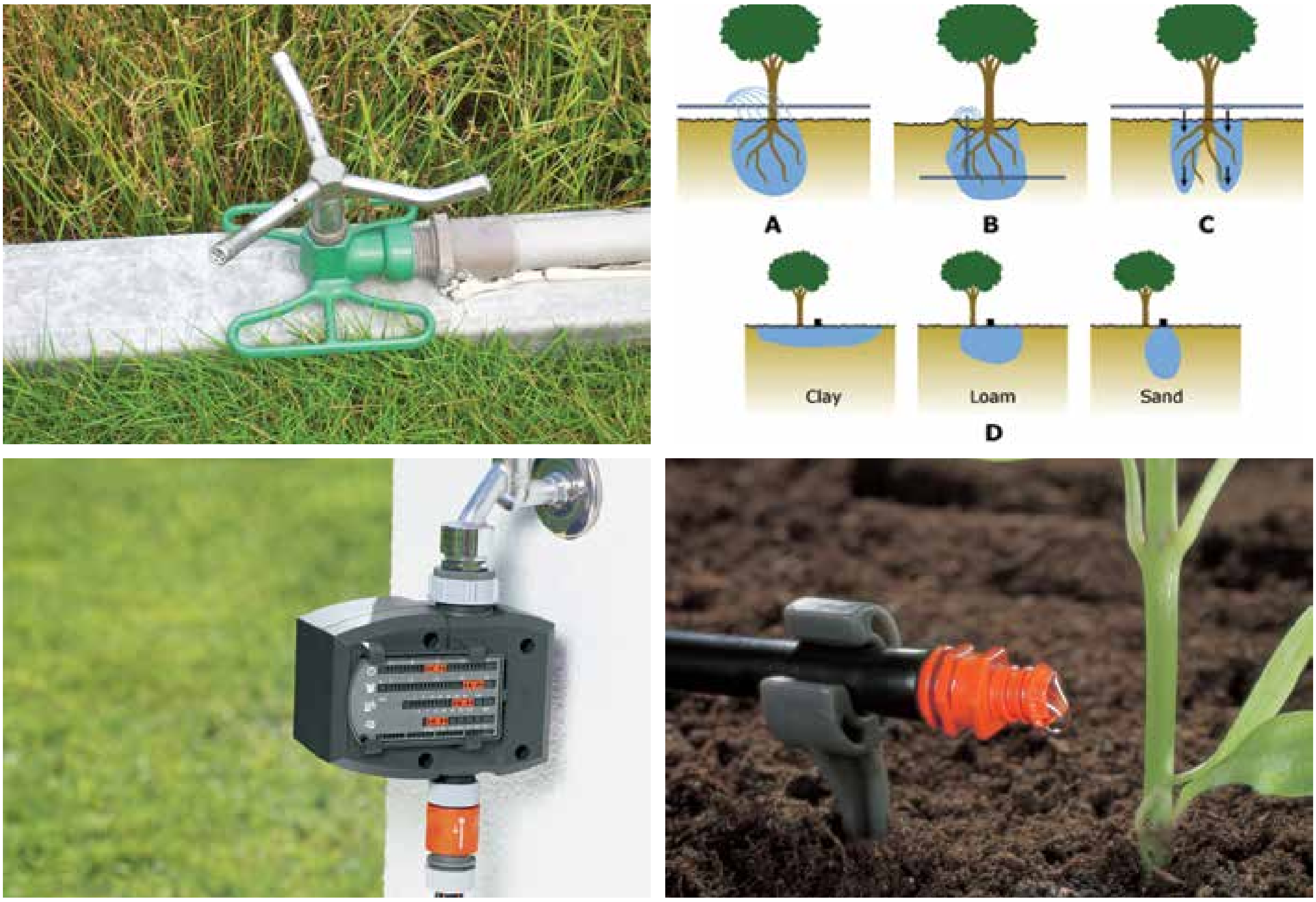


Figure 7.1 Irrigation methods for green roofs
Top left: Water sprinkler for irrigation
Top right: Drip irrigation system
Bottom left: Water control
Credit: Gardena www.gardena.com
Bottom right: Endline drip head
Credit: Gardena www.gardena.com

8 Project management

Project management is critical to delivering successful green roof installations. The client should employ a consultant to prepare a proposal that outlines the choice of green roof, technical requirements, building requirements, maintenance requirements, cost estimation and time schedule. Qualified professionals should be engaged to design the green roof system. Appendix A9 gives a checklist for considerations before starting a green roof project.

Scheduling works as per the project programme (particularly the waterproofing installation) and collaborating with the green roof supplier will be essential to ensuring that materials arrive on time, whilst minimising the time that plant materials are stored on site. The method of installation for the substrate and planting layer should be suited to the roof layout and objectives. Before installation works start, the integrity of the waterproof covering must be tested and approved. All drainage works, flashings etc. should be finished before the green roof covering is applied.

8.1 The role of professionals

Selecting professional consultants will depend on the function of the green roof, the size of the project, the location of the project and the green roof experience of the primary consultant and/or project instigator. A structural engineer may be required to determine the existing, or required, loading capacity of the roof. An architect may be required to coordinate the project as well as the design and detailing of the building and roof, including material specifications. A landscape architect may be required for the layout of the planting areas and the selection of the plants. A building services engineer (BSE) may be required to calculate the cooling and heating implications of the green roof, and to discuss integration with existing and proposed rooftop building services equipment, water/electricity supply and drainage needs. Depending on the primary function of the green roof, specialist consultants may also include a horticulturalist, a horticultural therapist, an ecologist or biologist, a roofing consultant, a planner, an artist and marketing/advertising professionals.

A building professional should verify the building requirements, considering the structural adequacy of the building or structure on which the green roof is constructed, any requirements for building alterations and whether statutory submission is needed. For example, in Hong Kong an authorised person (AP) and/or registered structural engineer (RSE) should be employed to prepare the plans and supervise the construction of building works in case a submission to the Buildings Authority is required. For a green roof project in a school, approval by the Education Bureau (EB) may be required. The EB's additional administrative rules about appointing an AP and tendering procedures for appointing a registered contractor should be followed. For students' accessibility, EB requires the roof to have a fence at least 2.5 m high, depending on factors such as the nature and extent of the green roof and the planning, design and intended use of the roof area.

8.2 Contractual matters

Ideally, a green roof system should come from a single source; that is, a single supplier or contractor that supplies components (with a warranty) that are engineered to work together from the membrane up through the plants. Mixing and matching system components is potentially risky because you are taking full responsibility for anything that goes wrong. It is important to include a two-year maintenance contract in the specification to make sure the roof is well cared for during that crucial time.

If the project is a shallower modular system with trays or a vegetative mat system, there might not be an actual design cost, as these modules and mats are usually pre-planted and pre-grown. If the project is a shallow (extensive) or deep (intensive) loose-laid system, design fees can reach 10–15% (or more) depending on the complexity of the project. A planting plan, materials plan, grading plan and lighting plan corresponding to the architectural roof plan and site survey findings, plus analysis from the structural engineering plan, will probably need to be generated. The consulting fee on green roof systems depends on the size and complexity of the project.

Administrative review and project approval might constitute 0–10% of the overall project cost. Depending on the size, location and complexity of the project, certain regulatory reviews might be required that have administrative fees associated with the project. Keeping a project on schedule is often extremely important to ensure a timely return in investment for the client. Project approval process, administrative meetings and regulatory reviews can result in costly project delays or waiting time if not coordinated carefully.

Installation can also make up 0–10% of the overall project cost. If the project is a shallower modular system with trays or a vegetative mat system, there might be only a minimum installation cost. Deeper and more complex projects will more than likely have a higher installation cost. Other factors that affect cost are access, size of project and approach for type of planting and implementation of components. Installation can sometimes be as expensive (or more expensive than) the material cost of the project.

It is important that the installing waterproofing contractor is aware that a green roof will be installed over the roof covering, thereby allowing the detailing (e.g. upstands) to accommodate the increased build-up. For existing buildings, it is important to have written confirmation from a professional engineer certifying that the structure is capable of bearing the additional load of a green roof system.

The ArchSD in Hong Kong has tried two procurement methods for green roof projects in government buildings, using small-quotation, lump-sum contracts. The first method is a term consultancy by which the main contractor will appoint a specialist green roof contractor with proven experience. The second method is a small consultancy with the architectural consultant as lead consultant for building works and the landscape architect consultant as sub-consultant for the green roof.

8.3 Costs of green roof systems

Cost and maintenance requirements are key considerations when evaluating green roof systems. The cost will vary depending on size, complexity, location and any financial incentives. Green roofs are always cost effective when considered over the lifetime of the building because they increase income and decrease costs. Green roofs are initially more expensive than traditional roof systems; however, both short- and long-term building owners reap rewards in several important ways, such as increased property values, improved building performance and, in the case of roof gardens, added usable space. When all of the benefits are considered, the payback of green roofs usually makes economic sense. Therefore, planning and funding of green roofs requires an understanding of lifecycle costs (from cradle to grave) and the related environmental benefits.

8.3.1 Cost evaluation

The cost of a green roof depends on various factors, including the type of green roof (e.g. extensive or intensive), green roof system build-up and different types of planting. Other important aspects include logistics, transporting materials, the roof slope and the entire roof size (the larger the green roof, the cheaper the cost on a square metre basis). Other cost items include design and specifications, project administration and site review, maintenance and the irrigation system. Table 8.1 shows the factors affecting the overall project cost of extensive and intensive green roof systems.

Table 8.1 Factors affecting the costs of green roof systems

Extensive green roofs	Intensive green roofs
▪ Access constraints to the site during construction. ▪ Whether the project is a new construction or a retrofit project. ▪ The slope of the roof. ▪ Status of the existing roof (if a retrofit project). ▪ The number and arrangement of rooftop utilities, affecting labour and wastage. ▪ The materials used, and the type of plant material used. ▪ Irrigation needs. ▪ Growing medium depth. ▪ Access or safety components that need to be added.	▪ Access constraints to the site during construction. ▪ The ratio of hard to soft landscaping. ▪ The amount of specialised thematic designs and materials, including water features, canopies, etc. ▪ Whether the green roof is part of a larger building contract; this affects the availability of building equipment already on site. For example, costs can be drastically affected if cranes are brought in just for landscaping. ▪ Whether the contract needs to be built in access-limiting stages; when a site is being used by the public (often requiring pedestrian diversions), this can increase costs. ▪ The size and maturity of the trees being installed and the type of vegetation being prescribed (palms, bamboo, trees). ▪ The depth of the topsoil. ▪ Irrigation needs. ▪ Lighting required. ▪ Access or safety components that need to be added.

Urbis Limited (2007) has estimated the green roof costs in Hong Kong as follows (based on the information up to 2007). (The cost estimate should be adjusted to current price level taking into account various factors that may affect the overall cost, such as market development of green roof projects, site and project constraint, and use of recycled water for irrigation.)

(Exchange rate: Euro 1 ≈ HK$10; UK£1 ≈ HK$12.5; US$ 1 ≈ HK$7.8)

- Capital costs:
  - intensive green roofs: HK$1000–5000/m^2 (market average: HK$2000/m^2)
  - extensive green roofs: HK$400–1000/m^2 (market average: HK$500/m^2).
- Recurrent costs:
  - intensive green roofs: HK$6.5–44/m^2/year (average: HK$20/m^2/year)
  - extensive green roofs: HK$0.8–2.25/m^2/year.

8.3.2 Incentive schemes

In the past, the cost related to the installation of a green roof has been high. As this industry develops, the initial cost of implementation will be reduced with standardised practices and programmes that allow consistent availability of products, suppliers and installers. Incentives provided by the public and private sectors, technology advances and integrated building designs could decrease the project cost and make green roofs more cost effective and attractive to a wider range of clients. In the future, green roofs may become a requirement for certain building types, or a source of yearly tax credits for retention of rainwater runoff from the site.

Some countries and cities with proactive governments and environmental organisations provide incentive schemes to co-fund part of the installation cost for green roofs and some cities also provide indirect and direct subsidies and ordinances. Three well-known examples are described below.

- Singapore: the Green Roof Incentive Scheme (GRIS) and Skyrise Greenery Incentive Scheme (SGIS) (www.skyrisegreenery.com) offer cash incentives of up to half the cost of installing green walls and green roofs on existing buildings.
- Germany: taxes are collected on anticipated stormwater control or usage fees and are used to cover constructing, maintaining and replacing stormwater management facilities. A reduction of 50–80% of this stormwater tax is allowed for using green roofs.
- Germany: an indirect subsidy allows developers to use green roofs as mitigation for the provision of open space. Local land development ordinances allow green roofs to compensate for lost open space at a ratio of 0.5 to 0.7. This creates a very attractive alternative in areas of high real-estate prices.

8.4 Regulatory measures and policies

Green roof systems are considered an extension of the roof system, so must comply with requirements for structural loading and moisture protection. If the green roof is accessible for more than routine maintenance—i.e. for tenants or public use—the design must also comply with requirements for occupancy, exiting, lighting, guardrails and barrier-free access. Some countries have adopted policies to require or encourage green roofs.

Green roof policies are important for encouraging applications and promoting the fast expansion of the green roof market. Direct financial incentives, reduced stormwater taxes, density relief and regulatory measures have been used (Shepard, 2010). In Japan (Tokyo), greenery installation to flat-roof areas is a legal requirement on new-build development. In Germany, an entire service industry has been formed around green roof installation, significantly reducing the initial costs. In the UK, policies encompassing urban renewal, construction, open space, nature conservation and drainage all have relevance to green roofs. In London, new planning policy has been established to promote living roofs and walls (Gedge *et al*., 2008).

In 2009 in Singapore the Urban Redevelopment Authority (URA) and National Parks Board (NParks) introduced initiatives to promote skyrise greenery, aiming for an extra 50 ha by 2030 (www.skyrisegreenery.com). First, the URA's Landscaping for Urban Spaces and High-rises (LUSH) programme actively facilitated the provision of greenery within the private realm by encouraging developers to incorporate both ground greenery and skyrise greenery in the form of sky terraces and rooftop gardens. Second, NParks introduced incentive schemes to encourage existing building owners to green their rooftops. Cash incentives of up to half the cost of installation are provided to encourage building owners to install green roofs. To help developers implement green roofs smoothly, NParks also provides technical advice on green roof technology.

In urban cities like Hong Kong, there is an urgent need to enhance the policy framework for green roofs and urban greening in order to support sustainable urban living space (BD, 2009). The policy measures might include financial incentives, development regulations, density bonus, land lease conditions, fast-track approval and streamlining. It is also important to establish the knowledge and expertise to properly specify, construct and approve green roofs—they should be constructed to acceptable minimum standards. Currently, German (FLL) standards are being used by most suppliers and installers and this is expected to continue. Once the green roof market has been successfully built up, it will be necessary to develop performance ratings to evaluate the effectiveness of green roofs in addressing various environmental attributes.

8.5 Green roof performance

The actual performance of green roof systems depends on a number of factors. There have been some research studies on thermal and energy performance (Bass and Baskaran, 2003; Hui, 2009; Niachou, *et al*., 2001), hydrologic or stormwater management performance (Carter and Jackson, 2007; Hui and Chu, 2009; Köhler, *et al*., 2001; Simmons, *et al*., 2008), as well as air-quality/pollution control (Currie and Bass, 2008; Yang, Yu and Gong, 2008); this research information is helpful for understanding and evaluating the potential and limitation of green roof systems. Figure 8.1 shows a green roof research facility in Canada for testing green roof performance.

To ensure that a green roof achieves its performance goals or performs its ecological function, it is necessary to examine the various performance aspects in a holistic manner. In Germany (Lawlor, *et al*., 2006), the FLL developed a performance rating system for green roofs to aid with regulatory measures to ensure compliance. The points-based system assesses the components and functions of the green roof. To obtain the base value, it takes the depth of the green roof system that can be penetrated by the plant roots and assigns 10 points for each centimetre of penetration. For example, if the depth is 10 cm, the system's base value is 100 points. From here, the system sets performance criteria for four further categories as shown below. People can use this tool to ensure that a green roof meets the desired ecological functions.

- Water retention capacity of the growing medium.
- Water retention capacity of the drainage layer.
- Number of plant species for extensive green roofs.
- Plant biomass or volume for intensive green roofs.

In Japan in 2005, the Organisation for Landscape and Urban Green Infrastructure established an evaluation system on green infrastructure—Social and Environmental Green Evaluation System (SEGES) (www.seges.jp). This method can be applied to all types of greening installations and considers the land use sustainability, green space management and greening functions for the assessment. It currently provides five levels of rating including Green Stage, Excellent Stage 1 to 3, and Superlative Stage.

More research is needed to investigate the performance of green roofs and determine the best strategy for designing green roof systems for other urban cities such as Hong Kong.

Figure 8.1 Green roof research facility at BCIT, Canada

References

ASTM (2006) ASTM Standard E 2400-06: *Standard Guide for Selection, Installation, and Maintenance of Plants for Vegetative (Green) Roof Systems* (West Conshohocken, PA: ASTM International)

ASTM (2011a) ASTM Standard E 2396-11: *Standard Test Method for Saturated Water Permeability of Granular Drainage Media (Falling-Head Method) for Vegetative (Green) Roof Systems* (West Conshohocken, PA: ASTM International)

ASTM (2011b) ASTM Standard E 2397-11: *Standard Practice for Determination of Dead Loads and Live Loads Associated with Vegetative (Green) Roof Systems* (West Conshohocken, PA: ASTM International)

ASTM (2011c) ASTM Standard E 2398-11: *Standard Test Method for Water Capture and Media Retention of Geocomposite Drain Layers for Vegetative (Green) Roof Systems* (West Conshohocken, PA: ASTM International)

ASTM (2011d) ASTM Standard E 2399-11: *Standard Test Method for Maximum Media Density for Dead Load Analysis of Vegetative (Green) Roof Systems* (West Conshohocken, PA: ASTM International)

Banting D, Doshi H, Li J, Missios P, Au A, Currie BA and Verrati M (2005) *Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto* (Toronto: Ryerson University)

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

BBQTS (2005) DB11/T 281-2005: *Code for Roof Greening* (Beijing: Bejing Bureau of Quality and Technical Supervision)

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

BD (2010) *Provision of Sky Garden in Refuge Floor: APP-122: Practice Notes for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers* (Hong Kong: Buildings Department)

BD (2011a) *Amenity Features: APP-42: Practice Notes for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers* (Hong Kong: Buildings Department)

BD (2011b) *Building Design to Foster a Quality and Sustainable Built Environment: APP-151, Practice Notes for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers* (Hong Kong: Buildings Department)

BD (2011c) *Code of Practice for Dead and Imposed Loads* (Hong Kong: Buildings Department)

BD (2011d) Sustainable Building Design Guidelines: APP-152: *Practice Notes for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers* (Hong Kong: Buildings Department)

BD, LandsD and PlanD (2011a) Joint Practice Note No 1: *Green and Innovative Buildings* (Hong Kong: Buildings Department, Lands Department and Planning Department)

BD, LandsD and PlanD (2011b) Joint Practice Note No 2: *Second Package of Incentives to Promote Green and Innovative Buildings* (Hong Kong: Buildings Department, Lands Department and Planning Department)

BEAM Society (2010a) *BEAM Plus for Existing Buildings: Version 1.1* (2010.04) (Hong Kong: BEAM Society)

BEAM Society (2010b) *BEAM Plus for New Buildings: Version 1.1* (2010.04) (Hong Kong: BEAM Society)

Cantor SL (2008) *Green Roofs in Sustainable Landscape Design* (New York: WW Norton and Co)

Carter T and Jackson CR (2007) 'Vegetated roofs for stormwater management at multiple spatial scales' *Landscape and Urban Planning* 80 (2007) 84–94

CEDD (2010) *Greening Master Plan* (Hong Kong: Civil Engineering and Development Department)

CUGE (2009a) CS A01: 2009: *Specifications for Soil Mixture for General Landscaping Use* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2009b) CS A02: 2009: *Specifications for Composts and Mulches* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2010a) CS B01: 2010: *Guidelines for Tropical Turfgrass Installation and Management* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2010b) CS E01: 2010: *Guidelines on Design Loads for Rooftop Greenery* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2010c) CS E02: 2010: *Design for Safety for Rooftop Greenery* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2010d) CS E03: 2010: *Guidelines on Substrate Layer for Rooftop Greenery* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2010e) CS E04: 2010: *Guidelines on Filter, Drainage and Root Penetration Barrier Layers for Rooftop Greenery* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2012a) CS E05: 2012: *Guidelines on Waterproofing for Rooftop Greenery* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2012b) CS E06: 2012: *Guidelines on Irrigation for Rooftop Greenery* (Singapore: Centre for Urban Greenery and Ecology)

CUGE (2012c) CS E07: 2012: *Guidelines on General Maintenance for Rooftop Greenery* (Singapore: Centre for Urban Greenery and Ecology)

Currie BA and Bass B (2008) 'Estimates of air pollution mitigation with green plants and green roofs using the UFORE model' *Urban Ecosystems* 11 (4) 409–422

DEVB and ENB (2009) *Green Government Buildings: Development Bureau Technical Circular 5/2009 and Environment Bureau Circular Memorandum 2/2009* (Hong Kong: Development Bureau and Environment Bureau)

Drivers Jonas and EDAW AECOM (2009) *Greater Manchester Green Roof Guidance* (Manchester: Commission for the New Economy, Manchester City Council)

DSD (2009) *Application of Green Roof in Wan Chai East and West Preliminary Treatment Works: Research and Development Item RD 1059* (Hong Kong: Project Management Division, Drainage Services Department)

Dubai Municipality (2009) *Green Roof Manual: Guidelines for Planning, Execution and Maintenance of Green Roof Various Applications* (UAE: Dubai Municipality, Government of Dubai)

Dunnett N and Kingsbury N (2008) *Planting Green Roofs and Living Walls* (revised and updated edition) (Oregon: Timber Press)

Dvorak B (2011) 'Comparative analysis of green roof guidelines and standards in Europe and North America' *Journal of Green Building* 6 (2) 170–191

Environa Studio (2010) *Green Roof Resource Manual* (Sydney: Sydney City Council)

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

FLL (2008) *Guidelines for the Planning, Construction and Maintenance of Green Roofing* (Bonn: Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.)

FM (2007) *FM Global Property Loss Prevention Data Sheets 1–35: Green Roof Systems* (Johnston, RI: Factory Mutual)

GBQTS (2007) DB440100/T 111-2007: *The Technical Code for Roof Greening* (Guangzhou: Guangzhou Bureau of Quality and Technical Supervision)

Gedge D, Newton J, Cradick K and Cooper P (2008) *Living Roofs and Walls: Technical Report: Supporting London Plan Policy* (London: Great London Authority)

Green Roof Organisation (2011) *The GRO Green Roof Code: Green Roof Code of Best Practice for the UK 2011* (Sheffield: Groundwork Sheffield) [At the time of writing *The GRO Green Roof Code* was in the process of being updated]

Groundwork Sheffield (2011) *Green Roof Guide* (Sheffield: Groundwork Sheffield)

Groundwork Sheffield (2010) *Green Roof Guidelines* (Sheffield: The Innovation Centre)

Hassell C and Coombes B (2007) *Green Roofs: CIBSE Knowledge Series KS11* (London: CIBSE)

Hui SCM (2006) 'Benefits and potential applications of green roof systems in Hong Kong' Proc. conf: *Second Megacities International Conference 2006*

Hui SCM (2009) *Study of Thermal and Energy Performance of Green Roof Systems: Final Report* (Hong Kong: Department of Mechanical Engineering, The University of Hong Kong)

Hui SCM (2010) 'Development of technical guidelines for green roof systems in Hong Kong' Proc. conf: *Joint Symposium 2010 on Low Carbon High Performance Buildings*

Hui SCM (2011) 'Green roof urban farming for buildings in high-density urban cities' Conf. paper at: *Hainan China World Green Roof Conference 2011*

Hui SCM and Chan HM (2008) 'Development of modular green roofs for high-density urban cities' Conf. paper at: *World Green Roof Congress 2008*

Hui SCM and Chan SC (2011) 'Integration of green roof and solar photovoltaic systems' Conf. paper at: *Joint Symposium 2011: Integrated Building Design in the New Era of Sustainability*

Hui SCM and Chu CHT (2009) 'Green roofs for stormwater mitigation in Hong Kong' Proc. conf: *Joint Symposium 2009: Design for Sustainable Performance*

IGRA (2008) *A Quick Guide to Green Roofs* (Berlin: International Green Roof Association)

Köhler M, Schmidt M, Grimme FW, Laar M and Gusmao F (2001) 'Urban water retention by greened roofs in temperate and tropical climate' Proc. conf: *38th IFLA World Congress*

Kumar R and Kaushik SC (2005) 'Performance evaluation of green roof and shading for thermal protection of buildings' *Building and Environment* 40 (11) 1505–1511

Lawlor G, Currie BA, Doshi H and Wieditz I (2006) *Green Roofs: A Resource Manual for Municipal Policy Makers* (Ottawa: Canada Mortgage and Housing Corporation)

Lim YA and Kishnani NT (2010) 'Building integrated agriculture: utilising rooftops for sustainable food crop cultivation in Singapore' *Journal of Green Building* 5 (2) 105–113

Liu KKY (2002) 'Energy efficiency and environmental benefits of rooftop gardens' *Construction Canada* 44 (2) 20–23

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

Liu K (2011) 'Retrofitting existing buildings with green roofs' In: *Construction Canada* 42–50

Loesken G (2009) 'Key criteria for creating green roof guidelines' In: R Appl and W Ansel (eds) Proc. conf: *International Green Roof Congress*

Loh S (2009) 'Green roofs – understanding their benefits for Australia' *Environment Design Guide* TEC 27 (Australian Institute of Architects)

Newton J, Gedge D, Early P and Wilson S (2007) *Building Greener: Guidance on the Use of Green Roofs, Green Walls and Complementary Features on Buildings* (London: Construction Industry Research Information Association)

Niachou A, Papkonstantinou K, Santamouris M, Tsangrassoulis A and Mihalakakou G (2001) 'Analysis of the green roof thermal properties and investigation of its energy performance' *Energy and Buildings* 33 719–729

NRCA (2009) *The NRCA Vegetative Roof Systems Manual* (2nd edition) (Rosemont, IL: National Roofing Contractors Association)

Oberlander CH, Whitelaw E and Matsuzaki E (2002) *Introductory Manual for Greening Roof* (Version 1.1) (Vancouver, BC: Public Works and Government Services)

Ong CL and Sia A (eds) (2002) *Handbook on Skyrise Greening in Sinagpore* (Singapore:

National Parks Board and Centre for Total Building Performance, School of Design and Environment National University of Singapore)

Organisation for Landscape and Urban Green Technology Development (1996) *Neo Green Space Design* (Volumes 1–4) (Tokyo: Seibundo Shinkosha Publishing) (in Japanese)

Organisation for Landscape and Urban Green Technology Development (1999) *Guide to Roof and Wall Green Technologies* (Tokyo: Printing Bureau, Ministry of Finance) (in Japanese)

Organisation for Landscape and Urban Green Technology Development (2000) *Green Roof Q&A* (Tokyo: Kajima Institute Publishing) (in Japanese)

Peck S and Kuhn M (2004) *Design Guidelines for Green Roofs* (Ontario: Ontario Association of Architects and Canada Mortgage and Housing Corporation)

Peck SW and van der Linde D (2010) 'System integration' *Eco-structure* September

Perkins M and Joyce D (2012) *Living Wall and Green Roof Plants for Australia* (Barton, ACT: Rural Industries Research and Development Corporation)

SBQTS (2009) DB440300/T 37-2009: *Code for the Design of Roof Greening* (Shenzhen: Shenzhen Bureau of Quality and Technical Supervision)

Shepard N (2010) *Green Roof Incentives: A 2010 Resource Guide* (Washington, DC: DC Greenworks)

Simmons MT, Gardiner B, Windhager S and Tinsley J (2008) 'Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and nonreflective roofs in a sub-tropical climate' *Urban Ecosystems* 11 (4) 339–348

Snodgrass EC and Snodgrass LL (2006) *Green Roof Plants: A Resource and Planting Guide* (Portland: Timber Press)

SPRI (2010a) ANSI/SPRI RP-14: *Wind Design Standard for Vegetative Roofing Systems* (Waltham, MA: Single Ply Roofing Industry)

SPRI (2010b) ANSI/SPRI VF-1: *External Fire Design Standard for Vegetative Roofs* (Waltham, MA: Single Ply Roofing Industry)

Tan PY and Sia A (2008) *A Selection of Plants for Green Roofs in Singapore* (2nd edition) (Singapore: National Parks Board)

Tolderlund L (2010) *Design Guidelines and Maintenance Manual for Green Roofs in the Semi-Arid and Arid West* (Toronto: Green Roofs for Healthy Cities)

Toronto Building (2010) *Toronto Green Roof Construction Standard: Supplementary Guidelines* (Toronto: Toronto Building)

Urbis Limited (2007) *Study on Green Roof Application in Hong Kong: Final Report* (Hong Kong: Architectural Services Department)

USGBC (2009) *LEED 2009 for New Construction and Major Renovations* (Washington, DC: US Green Building Council)

Velazquez L (2003) 'Modular green roof technology: an overview of two systems' Proc. conf: *First Annual Greening Rooftops for Sustainable Communities Conference*

Weiler S and Scholz-Barth K (2009) *Green Roof Systems: A Guide to the Planning, Design and Construction of Building Over Structure* (Hoboken, NJ and Chichester: John Wiley)

Wong NH and Chen Y (2009) *Tropical Urban Heat Islands: Climate, Buildings and Greenery* (London and New York: Taylor and Francis)

Wong NH, Tan PY and Chen Y (2007) 'Study of thermal performance of extensive rooftop greenery systems in the tropical climate' *Building and Environment* 42 (1) 25–54

Yang J, Yu Q and Gong P (2008) 'Quantifying air pollution removal by green roofs in Chicago' *Atmospheric Environment* 42 (31): 7266–7273

ZinCo (2000) *Green Roofs: Recommended Standards for Designing and Installation on Roofs: Planning Guide* (6th edition) (Unterensingen: ZinCo GmbH)

Abbreviations

AP	Authorised Person
ArchSD	Architectural Services Department, HKSARG
ASTM	American Society for Testing and Materials
BCIT	British Columbia Institute of Technology (Canada)
BD	Buildings Department, HKSARG
BEAM	Building Environmental Assessment Method
BREEAM	Building Research Establishment Environmental Assessment Method
BSE	Building Services Engineer
CEDD	Civil Engineering and Development Department, HKSARG
CIBSE	Chartered Institution of Building Services Engineers
CUGE	Centre for Urban Greenery and Ecology, Singapore
DEVB	Development Bureau, HKSARG
DSD	Drainage Services Department, HKSARG
EB	Education Bureau, HKSARG
ECF	Environment and Conservation Fund
EMSD	Electrical and Mechanical Services Department, HKSARG
ENB	Environment Bureau, HKSARG
FBB	Fachvereinigung Bauwerksbegrünung e.V. (German Green Roof Association)
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (Research Society for Landscape Development and Landscape Design)
GFA	Gross floor area
GRIS	Green Roof Incentive Scheme (Singapore)
GRO	Green Roof Organisation (UK)
HKPSG	Hong Kong Planning Standards and Guidelines
HKSAR	Hong Kong Special Administrative Region
HKSARG	Hong Kong Special Administrative Region Government
HKU	The University of Hong Kong

HVAC	Heating, ventilating and air conditioning
IGRA	International Green Roofs Association
JPN	Joint Practice Notes
LandsD	Lands Department, HKSARG
LEED	Leadership in Energy and Environmental Design
LUSH	Landscaping for Urban Spaces and High-rises programme (Singapore)
NParks	National Parks Board (Singapore)
NRCA	National Roofing Contractors Association (USA)
PlanD	Planning Department, HKSARG
PNAP	Practice Notes for Authorised Persons, Registered Structural Engineers and Registered Geotechnical Engineers
PV	Photovoltaic
RSE	Registered Structural Engineer
SC	Site coverage
SEGES	Social and Environmental Green Evaluation System (Japan)
SGIS	Skyrise Greenery Incentive Scheme (Singapore)
SPRI	Single Ply Roofing Industry (USA)
UHI	Urban heat island
URA	Urban Redevelopment Authority (Singapore)
USGBC	U.S. Green Building Council

Appendix A1: Useful websites and resources

International

European Federation of Green Roof Associations (EFB): www.efb-greenroof.eu

Green Roofs for Healthy Cities: www.greenroofs.org

Greenroofs.com: The Resource Portal for Green Roofs: www.greenroofs.com

International Green Roof Association (IGRA): www.igra-world.com

International Promotion Centre for Vertical Planting (China): www.greenrooftops.cn

LivingRoofs: www.livingroofs.co.uk

World Green Roof Congress: www.worldgreenroofcongress.com

World Green Infrastructure Network (WGIN): www.worldgreenroof.org

Canada

Centre for Architectural Ecology, British Columbia Institute of Technology (BCIT): http://commons.bcit.ca/greenroof/

Germany

FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau) (Landscape Research, Development and Construction Society): www.fll.de

FBB (Fachvereinigung Bauwerksbegrünung e.V.) (German Green Roof Association): ww.fbb.de

Green Roof Centre of Excellence, Neubrandenburg: www.gruendach-mv.de/

Hong Kong

Development Bureau's Greening website: www.greening.gov.hk

Greening Master Plan (GMP), Civil Engineering and Development Department: www.cedd.gov.hk/eng/greening

HKU Green Roof Research: www.hku.hk/bse/greenroof

Hong Kong Green Building Council (HKGBC): www.hkgbc.org.hk

Japan

Organization for Landscape and Urban Green Infrastructure (formerly, Organisation for Landscape and Urban Green Technology Development (Urban Green Tech Japan) and Urban Green Space Development Foundation): www.urbangreen.or.jp

Social and Environmental Green Evaluation System (SEGES): www.seges.jp

Singapore

Centre for Urban Greenery and Ecology: www.cuge.com.sg

National Parks Board: www.nparks.gov.sg

Skyrise Greenery: www.skyrisegreenery.com

Plant Resources: www.skyrisegreenery.com/index.php/home/plant_info

UK

Green Roof Centre, Sheffield: www.thegreenroofcentre.co.uk

Green Roof Guidelines: www.greenroofguide.co.uk

USA

Extensive Vegetative Roofs (Whole Building Design Guide): www.wbdg.org/resources/greenroofs.php

Green Roof Research Program at Michigan State University: www.hrt.msu.edu/greenroof

Appendix A2: Different types of green roof systems

(Adapted from Green Roof Organisation (2011), Groundwork Sheffield (2011) and Loh (2009))

A green roof is a roof with vegetation integrated into its design. The term 'green roof' usually refers to an engineered system, thus many people would exclude lichen growing on roofs unintentionally. There are three main types of green roof systems.

1. Extensive green roof systems have 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.
2. Intensive green roof systems have system profiles ranging 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 (although they require more maintenance).
3. Semi-intensive or semi-extensive or simple intensive green roof systems include features of both intensive and extensive green roofs. They are of slightly greater depth than extensive systems (100–200 mm), which allows a greater diversity of plants to be grown and local habitats recreated. Based on the same principles as extensive roofs they are lightweight and generally low maintenance.

There are also some variations of the above. For example, sedum modular or mat systems, sedum substrate-based systems and wildflower and sedum substrate-based systems are used in Europe for describing extensive green roofs.

Since the advent of green roofs, a green roofs industry has developed and many other variations of green roofs now exist. Some of the terms are described below.

- Super lightweight green roofs have minimum loadings and consist of a thin (12 mm) drainage board, a filter fleece/water retention mat and pre-grown vegetated mat about 25 mm in thickness. They are suitable for some retrofit projects but have limited vegetation diversity.
- Built-in or integrated green roofs have green roof components installed as a series of layers.
- Modular green roofs are partially assembled off-site and installed in units. Some modular systems feature plastic or metal trays that are filled with growing medium and placed on the rooftop. Plants can be grown in these trays before or after installation. Other systems feature plants pre-grown in mats that are laid onto the roof surface.
- Sedum roofs are usually pre-grown sedum mats based on 20 mm of substrate or systems of greater substrate depth (standard depth = 70 mm) in which sedums can be seeded or planted.
- Meadow roofs are based on 70–100 mm substrate depth.

They involve the use of seeded or planted low, drought-tolerant grasses, perennials and alpines. These can be native or ornamental species.

- Brown or biodiversity roofs are a low-maintenance roof made of gravel or recycled material, such as crushed brick or concrete, with a small amount of soil providing habitat for certain types of plant and insect life, and some moss-covered roofs. Such roofs are designed to recreate natural and often local habitats rich in birds, plants and insects. This is often done by using the by-products of the development process such as rubble and subsoil, which are left to colonise naturally over time or seeded with wildflowers.
- Wetland green roofs function as a wetland ecosystem usually in conjunction with greywater recycling of the building they cover.
- Rooftop gardens do not have planting integrated into the roof system, and thus these are technically not classified as green roofs. However, sometimes there is no clear distinction, as some rooftop gardens have an amount of intensive or extensive planting together with container planting and permeable surfaces. Green roofs are not just confined to rooftops but include gardens built on building podia, 'sky gardens' (a Singaporean term), which can occur at mid-levels of building, and apartment balcony gardens.
- Urban agriculture include examples of rooftops being used for aquaponic or hydroponic food production using either intensive green roof systems or equipment situated on rooftops. When cultivation uses containers, the term 'green roofs' is used loosely.

Extract by Susan Loh (2009) Content owned by the Australian Institute of Architects. First published in the *Environment Design Guide* May 2009

Appendix A3: Technical guidelines and codes

Australia

Green Roof Resource Manual (Environa Studio, 2010)

'Green roofs – understanding their benefits for Australia' *Environment Design Guide* (Loh, 2009)

Canada

Design Guidelines for Green Roofs (Peck and Kuhn, 2004)

Design Guidelines and Maintenance Manual for Green Roofs in the Semi-arid and Arid West (Tolderlund, 2010)

Green Roofs: A Resource Manual for Municipal Policy Makers (Lawlor *et al*., 2006)

Introductory Manual for Greening Roof (Oberlander, Whitelaw and Matsuzaki, 2002)

Toronto Green Roof Construction Standard: Supplementary Guidelines (Toronto Building, 2010)

China

DB11/T 281-2005: *Code for Roof Greening* (BBQTS, 2005)

DB440100/T 111-2007: *The Technical Code for Roof Greening* (GBQTS, 2007)

DB440300/T 37-2009: *Code for the Design of Roof Greening* (SBQTS, 2009)

Germany

Guidelines for the Planning, Construction and Maintenance of Green Roofing (FLL, 2008)

Guidelines for the Planning, Execution and Upkeep of Green-roof Sites: Roof-greening Guidelines (FLL, 2004)

Hong Kong

Study on Green Roof Application in Hong Kong: Final Report (Urbis Limited, 2007)

A Quick Guide to Green Roofs (IGRA, 2008)

Japan

Guide to Roof and Wall Green Technologies (Organisation for Landscape and Urban Green Technology Development, 1999)

Singapore

Handbook on Skyrise Greening in Sinagpore (Ong and Sia, 2002)

A Selection of Plants for Green Roofs in Singapore (Tan and Sia, 2008)

UAE

Green Roof Manual: Guidelines for Planning, Execution and Maintenance of Green Roof Various Applications (Dubai Municipality, 2009)

UK

Greater Manchester Green Roof Guidance (Drivers Jonas and EDAW AECOM, 2009)

The GRO Green Roof Code: Green Roof Code of Best Practice for the UK 2011 (Green Roof Organisation, 2011) [At the time of writing *The GRO Green Roof Code* was in the process of being updated]

Living Roofs and Walls: Technical Report: Supporting London Plan Policy (Gedge *et al*., 2008)

Green Roof Guidelines (Groundwork Sheffield, 2010)

Green Roofs: CIBSE Knowledge Series KS11 (Hassell and Coombes, 2007)

Building Greener: Guidance on the Use of Green Roofs, Green Walls and Complementary Features on Buildings (Newton *et al*., 2007)

USA

FM Global Property Loss Prevention Data Sheets 1–35: Green Roof Systems (FM, 2007)

The NRCA Vegetative Roof Systems Manual (NRCA, 2009)

(See references section for details.)

Appendix A4: Technical standards for green roofs

American Society for Testing and Materials (ASTM) USA: www.astm.org

ASTM Standard E 2396-11: *Standard Test Method for Saturated Water Permeability of Granular Drainage Media [Falling-Head Method] for Vegetative (Green) Roof Systems* (ASTM, 2011a)

ASTM Standard E 2397-11: *Standard Practice for Determination of Dead Loads and Live Loads Associated with Vegetative (Green) Roof Systems* (ASTM, 2011b)

ASTM Standard E 2398-11: *Standard Test Method for Water Capture and Media Retention of Geocomposite Drain Layers for Vegetative (Green) Roof Systems* (ASTM, 2011c)

ASTM Standard E 2399-11: *Standard Test Method for Maximum Media Density for Dead Load Analysis of Vegetative (Green) Roof Systems* (ASTM, 2011d)

ASTM Standard E 2400-06: *Standard Guide for Selection, Installation, and Maintenance of Plants for Vegetative (Green) Roof System* (ASTM, 2006)

Centre for Urban Greenery and Ecology (CUGE) Singapore: www.cuge.com.sg

CS E05: 2012: *Guidelines on Waterproofing For Rooftop Greenery* (CUGE, 2012a)

CS E06: 2012: *Guidelines on Irrigation For Rooftop Greenery* (CUGE, 2012b)

CS E07: 2012: *Guidelines on General Maintenance for Rooftop Greenery* (CUGE, 2012c)

CS B01: 2010: *Guidelines for Tropical Turfgrass Installation and Management* (CUGE, 2010a)

CS E01: 2010: *Guidelines on Design Loads for Rooftop Greenery* (CUGE, 2010b)

CS E02: 2010: *Design for Safety for Rooftop Greenery* (CUGE, 2010c)

CS E03: 2010: *Guidelines on Substrate Layer for Rooftop Greenery* (CUGE, 2010d)

CS E04: 2010: *Guidelines on Filter, Drainage and Root Penetration Barrier Layers For Rooftop Greenery* (CUGE, 2010e)

CS A01: 2009: *Specifications For Soil Mixture For General Landscaping Use* (CUGE, 2009a)

CS A02: 2009: *Specifications for Composts and Mulches* (CUGE, 2009b)

Single Ply Roofing Industry (SPRI) USA: www.spri.org

ANSI/SPRI RP-14: *Wind Design Standard for Vegetative Roofing Systems* (SPRI, 2010a)

ANSI/SPRI VF-1: *External Fire Design Standard for Vegetative Roofs* (SPRI, 2010b)

Toronto Building Canada: www.toronto.ca

Toronto Green Roof Construction Standard: Supplementary Guidelines (Toronto Building, 2010)

Appendix A5: Checklists for green roof planning

(Adapted from International Green Roof Association (IGRA): www.igra-world.com)

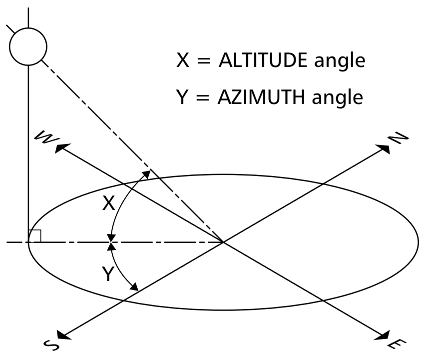
Construction engineering	Vegetation technology
▪ Roof substructure: substructure (reinforced concrete, wooden substructure, metal sheeting, etc.). ▪ Waterproofing: refurbishment or new construction. ▪ Roof parapets, roof penetrations and adjacent building parts: roof upstand and perimeter heights. ▪ Roof slope: normal green roof system build-up, absorption of shear and erosion forces. ▪ Roof construction: roof construction, thermal insulation, load bearing capacity. ▪ Assumed load: area loads through green roof system build-up and usage of the roof. ▪ Wind uplift: local wind effects, security measures. ▪ Roof drainage: drainage devices, rainfall, roof outlets. ▪ Irrigation: water connections, dam-up irrigation. ▪ Fire prevention: 'hard roofing', preventive protection. ▪ Accident prevention: fall protection. ▪ Roof access: installation, service and maintenance. ▪ Additional functions: thermal insulation, usage of the roof, rainwater and solar energy. ▪ Approval: building regulations.	▪ Local conditions: climate, microclimate, rainfall, roof height, roof slope, roof exposure. ▪ Desired green roof type: extensive green roof, semi-intensive green roof, intensive green roof. ▪ System build-up: functional layers: root barrier, protection layer, drainage layer, filter layer, growing medium, plant level. ▪ Plant selection: seeds, plants and vegetation of extensive green roofs and intensive green roofs. ▪ Different types of planting: seeding, cuttings, root ball plants, pre-cultivated vegetation mats. ▪ Maintenance and support: installation maintenance, development maintenance, upkeep maintenance. ▪ Water retention: water retention capacity, water runoff coefficient. ▪ Costs/subsidies: costs, government subsidies or other funds.

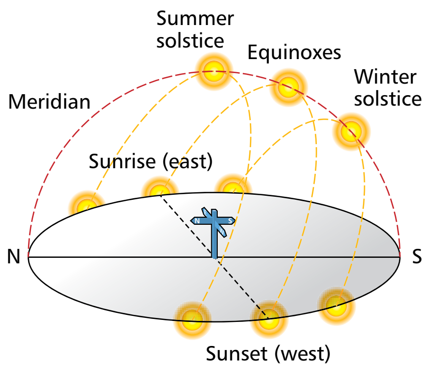
Green roof design checklist for Hong Kong: planning and feasibility
(Urbis Limited, 2007)

Category	Checklist questions
1. General	▪ What are the client's objectives for implementing a green roof? What are the city's main objectives for implementing green roofs? ▪ What kind of budget does the client have for both capital and recurrent costs? ▪ Who will see or appreciate the green roof? ▪ Is a green roof justified in the local context? ▪ Will the green roof be applied to special structures with special maintenance requirements or special access?
2. Type of roof	▪ Is the roof new, existing or in need of replacement or major repair? ▪ Can the existing waterproofing accommodate new layers and workmanship above without the need for new waterproofing? If so, who takes responsibility for the waterproofing?
3. Roof space	▪ Is there sufficient space on the roof to incorporate a significant area of plants, access pathways, rooftop utilities, safety railings or devices, and access via ladders or staircases, etc.? ▪ On new buildings, have the rooftop utilities been arranged to optimise the functional open space and to maximise the amount of greening?
4. Roof pitch	▪ Is or will the roof be flat or sloped? ▪ Has slippage of the growing medium been considered? ▪ How is drainage affected by the slope? ▪ Have the surface flows and water penetration rates been considered? Is the drainage layer below the growing substrate capable of removing excess water effectively?
5. Wind and climate	▪ Will severe winds be a problem? ▪ Have the wind limits of the site been determined? ▪ Are the green roof layers vulnerable to wind shear? ▪ Does the waterproofing layer need to be bonded to the roof beneath? ▪ Has the wind erosion of the soil mix been considered? ▪ Has the staking or weighting down of trees been considered? If so, how does this interface with the waterproof layer if it needs to connect directly to the structure? ▪ Are additional lightning conductors needed to avoid striking people or trees?
6. Accessibility	▪ Is or will the roof be accessible or inaccessible? ▪ How will the roof be accessed? ▪ If the roof is to be accessible, does it have space and loading capacity for additional railings, lights, paving, etc.? ▪ If accessible by the public will it be secure and safe? ▪ Have durable lightweight materials been used for the walkways?
7. Structural limits	▪ What are the structural loading limits of the roof? ▪ Have the loading calculations been done by a registered structural engineer or suitably qualified person? ▪ Has the dead load included all components (structure, paving, pipes, HVACs, etc)? ▪ Have the live load estimates included all components (rain, wind, people)? ▪ Has the dead weight of the green roof materials and plants been included? Do the soil substrate weights include moisture content at saturation point? ▪ Has plant weight at maturity been included, particularly for trees? ▪ Have maximum loading capacities for the roof been separated into different areas? ▪ Are polystyrene or other lightweight materials being used to increased depth without adding significant weight? ▪ Has the green roof manufacturer provided detailed information and attested to the fully saturated weight? ▪ Will any roofing components be removed from the roof, which allows for additional weight?
8. General design	▪ Have structural joints been incorporated into the green roof design from the beginning? ▪ Have maintenance paths been incorporated as part of the design?

Appendix A6: Sun path diagram for Hong Kong and shading study

Hong Kong is located at latitude 22° 18 ’ north and longitude 114° 10 ’ east (this refers to the weather station at Tsimshatsui, Kowloon).





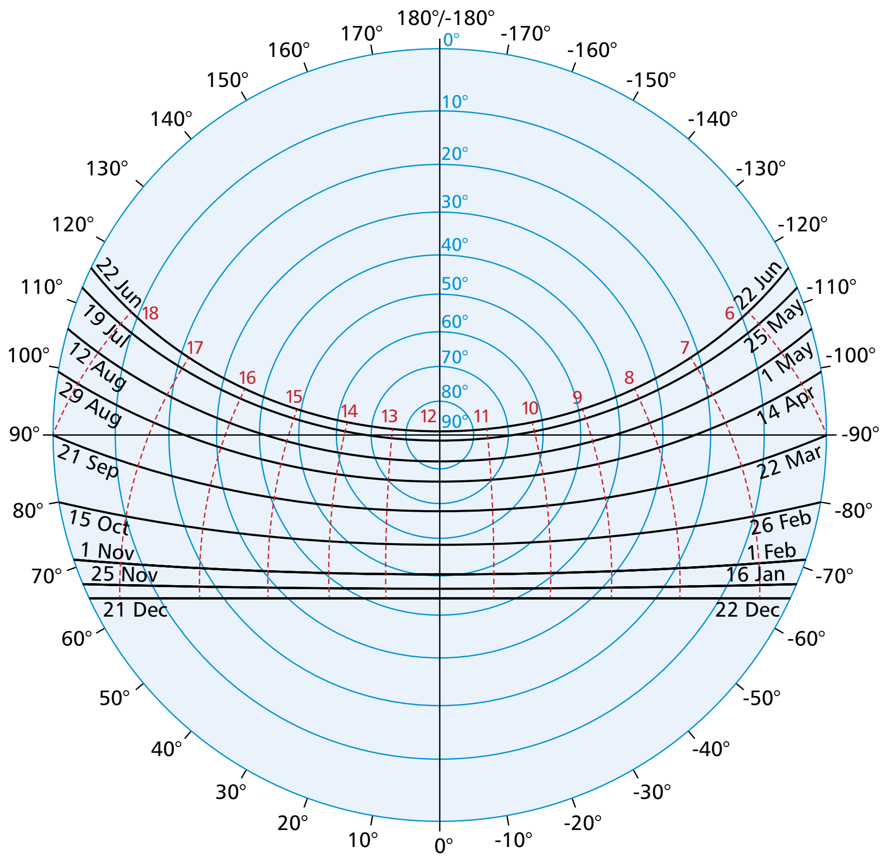


Figure A6.1 Example of sun path analysis and shading mask study (using Ecotect)
Credit: Autodesk screen shots reprinted with the permission of Autodesk, Inc

Further information

The Sun and Building Design Process I, II:
www.arch.hku.hk/~kpcheung/teaching/lecture/65156-8.htm

Shading Design (Ecotect): http://wiki.naturalfrequency.com/wiki/Shading_Design

Appendix A7: Design considerations for pitched green roofs

Technical requirements

Root-resistant waterproofing is necessary for pitched green roofs; installing an additional root barrier requires much effort and increases the risk of slippage. Stable abutments have to be installed on the eaves edges to transfer shear forces from the green roof system build-up and the additional rainwater or snow load into the roof construction. Additional shear barriers may be necessary to transfer the shear forces, depending on the roof slope and the roof length.

As the slope increases, the green roof system build-up becomes more complicated and the substrate has to be protected from erosion—plastic grid elements can be used for this purpose. Even though it is possible to build pitched green roofs with a slope of 45°, it is not recommended that it exceeds 30° due to significant limited accessibility for upkeep and maintenance.

Plant selection

The success of the landscaping on pitched roofs depends on the plants. Appropriate selection of plants is important. Fast surface coverage is the highest priority. A dense planting of root-ball plants or pre-cultivated vegetation mats are used in cases of steep slopes and allow for rapid coverage. It is also important to consider the exposure of the roof area, the slope and the location of the building when selecting plants. Perennials and grasses can be used for pitched green roofs, whereas sedum is the most suitable for pitched roofs due to the species' high water-retention capacity and erosion protection. The water runoff is much faster on pitched roofs compared with flat roofs. It is advisable to plan for an additional irrigation system to provide water during dry periods. The irrigation can be provided either by drip irrigation or by sprinkler systems.

Wind/solar exposure

A sloped roof is subject to more adverse conditions than a flat roof, which may be protected by parapet walls or other sheltering devices. It is essential to analyse sloped roofs for solar and wind exposure and the variability that may affect the roofing system. Since areas of intense sun or shade will change throughout the year, it is necessary to choose plant materials that can acclimatise to the extremes in temperature and light in highly variable areas. Wind may cause the growing medium to erode while plant cover is being established and it may be beneficial to include an erosion protection layer.

Make sure the roof will stay in place

The most critical component of any sloped green roof is the confinement system, which holds the growing medium in place during the roof's early stages of development. If not properly secured, a pitched vegetated roof can erode and slip under heavy rain, excessive irrigation or poor plant growth; this becomes more likely as the pitch of the roof increases. Different strategies can be employed to distribute the weight. Some of the considerations that need to be addressed are inconsistent drainage, irrigation imbalance and shear force of gravity, potentially causing the roofing system to be unstable.

There are several approaches to designing a confinement system. Cellular confinement systems are installed on top of the drainage mat and feature flexible open cells into which the growing medium is poured. The result is a fully supported growing medium up to 200 mm in height. The systems are embedded in the growing medium in a similar way. The webbing, which is no thicker than 25 mm, is sandwiched between two layers of soil. As the roots grow, they become entwined within the thin webbing material, producing a stable cover. This material works well because the roots usually become entwined within two weeks, and the growing medium is kept in place.

For low-slope systems, an erosion mat may suffice. Common with roadside landscaping projects, an erosion mat is usually manufactured using organic materials such as jute, wood or straw and held together with synthetic mesh or strand. The mat is installed on top of the soil surface; openings are cut where the vegetation is planted. Erosion mats are designed to decay after one to three years, when the vegetation is fully mature.

Another method is to terrace the roof. Usually this approach installs edging bars at regular distance (e.g. 4 m) so that if any soil slips, it will get caught by one of the bars.

Pay careful attention to peaks and valleys

Irrigation can be difficult with sloped systems because the water tends to filter down the roof quickly. As a result, vegetation near the top of the roof can lack vital moisture, while plants near the bottom often get too much as the water ponds and pools. To address this issue, the designer may plant water-loving vegetation at the bottom of the roof and varieties suited to arid soil at the top of the slope. The designer may also consider installing thicker growing medium near the top of slopes, as this area will dry out first. Some suppliers advise the designer to install a moisture-retention mat underneath the soil so that the vegetation has more time to feed.

Specify a high-performance waterproofing membrane

It is a mistake to think that water will not pool if the roof has a slope. The green roof should be treated as if it were a low-slope roof and a good, continuous waterproofing membrane should be used.

Appendix A8: Checklist for green roof maintenance

(Adapted from Tolderlund, 2010)

A green roof maintenance manual and/or maintenance agreement considering all relevant components and details should be written for each individual green roof project. A typical maintenance manual/maintenance agreement should, at a minimum, address the following points.

Fertilisation/spraying

- How often will plant material (overall roof and/or specific planter) be fertilised?
- What type of fertiliser should be used? Should it be from a specific provider?
- Are there any particular applications for specific plant needs and seasonal colour?
- Will insects be treated with horticultural oil or detergent-based insecticides or pesticides?
- Will there be a need for aerobic bacterial treatment?

Pruning

- How often will plant material be pruned and deadheaded?
- Will clippings and dead leaves be composted? Where?

Weed control

- Prepare for weeds in the dormant season by applying pre-emergence applications.
- How often will planters be manually weeded?

Clean-up

- How often will drainage outlets, water features and filters be cleaned?
- How often will entrances, planter edges, paths, etc. be cleaned?

Maintenance of furniture, paths, decking, planters, railings

- What products are recommended for upkeep of planter edges, furniture, decking, etc.?
- What products are not recommended due to potential chemical effect on other components of the roof assembly?
- What are the specific recommendations for which tools to use (and not use) for the upkeep and maintenance?
- Where are maintenance tools, ladder, hoses, security harnesses and other equipment stored?

Watering

- How will the roof plants be irrigated—hand watering and/or irrigation system?
- How frequently will the roof plants be irrigated—during the summer?
- Will there be hand watering during the winter? How frequently?
- How often will the controller system and operating system be checked?
- Are irrigation systems installed with a back-flow preventer valve that can be drained in case of a freeze?
- Are there any specific requirements for upkeep and clean-up of water features?
- What is the typical lifespan of plants used on the green roof?

Seasonal recommendations

- Are there recommendations for or against seasonal soil amendments and/or adding mulching material?
- How often will biomass be removed if needed?
- How often will control burning be conducted if needed?

General information

- Create a contact list for all parties involved in the design, implementation and maintenance of the green roof, and keep it up to date.

Extract by: Leila Tolderlund, Research Associate and Senior Instructor, University of Colorado Denver, Department of Landscape and Architecture

Appendix A9: Checklist of considerations before starting a green roof project

(Adapted from Tolderlund, 2010)

1. Client expectations
2. Climate and geographical location/wind uplift during and after construction
3. Building's intended current (and future) use and design life
4. Structural analysis including building movement
5. Snow loads and water retention loads
6. Exterior and interior temperature, humidity and use conditions
7. Green roof system type including overburden
8. Green roof waterproofing membrane
9. Penetrations
10. Slope and drainage
11. Type and condition of growing medium
12. Type and amount of insulation, protection and drainage needed
13. Worker safety
14. Local code requirements
15. Need for ventilation during installation
16. Compatibility with adjacent building and/or system components
17. Construction sequence
18. Construction traffic
19. Accessibility and building configuration
20. Odour generated by certain system application methods
21. Considerations of green building certification assessment
22. Future maintenance of all green roof components (vegetation, drains, etc.)
23. Potential future building additions

Extract by: Leila Tolderlund, Research Associate and Senior Instructor, University of Colorado Denver, Department of Landscape and Architecture

Appendix A10: Case studies in Hong Kong

Case study 1:	Hong Kong Wetland Park Phase II: Visitor Centre
Address:	Wetland Park Road, Tin Shui Wai, New Territories
Building type:	Eco-tourist visitor centre
Completion:	2005
Total floor area:	10 000 m² (concealed beneath the landscape, giving the impression of a green hill rising above the entry plaza)
Green roof area:	Approximately 10 000 m² (sloping lawns)
Green roof type:	Intensive and semi-intensive

Figure A10.1 Site map
Credit: www.centamap.com

Figure A10.2 Hong Kong Wetland Park Phase II: Visitor Centre
Credit: Architectural Services Department

Figure A10.3 (above) Hong Kong Wetland Park Phase II: Visitor Centre
Credit: Architectural Services Department

Figure A10.4 Hong Kong Wetland Park Phase II: Visitor Centre
Credit: Architectural Services Department

Case study 2:	**Rehabilitation Block at Tuen Mun Hospital Phase II**
Address:	23 Tsing Chung Koon Road, Tuen Mun, New Territories
Building type:	Hospital
Completion:	June 2007 (new building block)
Site area:	10 761 m^2
Green roof area:	717 m^2 (distributed on four levels)
Green roof category:	Extensive, semi-intensive and planters
Media depth:	400–600 mm thick
Type of membrane:	Mira drain system with 50 mm styrotherm insulation

Figure A10.5 Site map
Credit: www.centamap.com

Typical plant materials (4/F Podium)

Tree	▪ Ficus benjamina ▪ Ficus benjamina 'variegata' ▪ Terminalia mantalyi var
Shrub	▪ Brunfelsia calycina ▪ Duranta repens 'variegata' ▪ Spathiphyllum x clevelandii
Groundcover	▪ Asparagus densiflorus 'myers' ▪ Arachis pintoi 'golden glory' ▪ Syngonium podophyllum 'variegatum'

Figure A10.6 Rehabilitation Block at Tuen Mun Hospital Phase II: 4/F Podium
Credit: Architectural Services Department

Figure A10.7 (above) Rehabilitation Block at Tuen Mun Hospital Phase II:
Left: 4/F Podium
Right: 12/F Podium
Credit: Architectural Services Department

Figure A10.8 Rehabilitation Block at Tuen Mun Hospital Phase II: 5/F Podium
Credit: Architectural Services Department

Figure A10.9 Rehabilitation Block at Tuen Mun Hospital Phase II: 2/F Podium
Credit: Architectural Services Department

Figure A10.10 Belilios Public School
Credit: Belilios Public School

Case study 3:	**Belilios Public School**
Address:	51 Tin Hau Temple Road, North Point, Hong Kong (www.belilios.net)
Building type:	Secondary school
Completion:	July 2010 (retrofit project)
Green roof area:	800 m^2
Green roof category:	Extensive (because of limitation of roof loading)
Site constraint:	No noisy work during school time that affected school operation. The final solution was to adopt a self-protective waterproofing membrane directly applied on existing finishes to avoid noisy work caused by demolition activities.

Problem encountered and solution

When designing the green roof, consideration was given to the compliance of statutory regulations, safety issues, surface discharge and hygiene problems. First, as the height of the parapet wall was reduced to less than 1.1 m (the statutory requirement) because the finished floor level was raised when the green roof was installed, additional railings had to be installed at the peripheral parapet wall. Second, in order to ensure safety, tailor-made channel gratings were installed to overcome the level difference at the open rainwater channel. Third, to prevent the hygiene problem of stagnant water after irrigation, additional discharge water channels were provided.

Figure A10.11 Site map
Credit: www.centamap.com

Figure A10.12 Belilios Public School
Credit: Architectural Services Department

Appendix A11: Case studies in other countries

Case study 1:	California Academy of Sciences, San Francisco, California, USA
Year:	2008
Building type:	Educational
Green roof type:	Extensive, test/research
System:	Custom
Green roof:	10 780 m²
Waterproofing:	2550 m²
Slope:	65%
Access:	Inaccessible, with a public viewing platform

Figure A11.1 California Academy of Sciences

Figure A11.2 California Academy of Sciences
Credit: American Hydrotech, Inc

Designers/manufacturers

- Green roof consultant: Rana Creek Living Architecture
- Ecological consultant: Paul Kephart, Rana Creek
- Architect: Renzo Piano Building Workshop
- Architect: Chong Partners Architecture
- Engineering and sustainability consulting: Arup
- Landscape architecture: SWA Group
- General contractor: Webcor Builders
- Waterproofing: American Hydrotech
- Building envelope/waterproofing design: Simpson Gumpertz and Heger
- Senior curator of botany: Frank Almeda, California Academy of Sciences
- Modular green roof system: BioTray

Awards

- 2008 Green Roofs for Healthy Cities Award of Excellence, Extensive Institutional Category
- 2009 ASLA Professional Award, General Design Category
- LEED Platinum-rated museum

Planting and maintenance

- Modular trays of plant material pre-grown and installed (BioTray, a biodegradable, reinforced, modular propagation tray made from rapidly renewable coconut coir fibers).
- Maintenance is controlled by replacing and rotating individual trays.

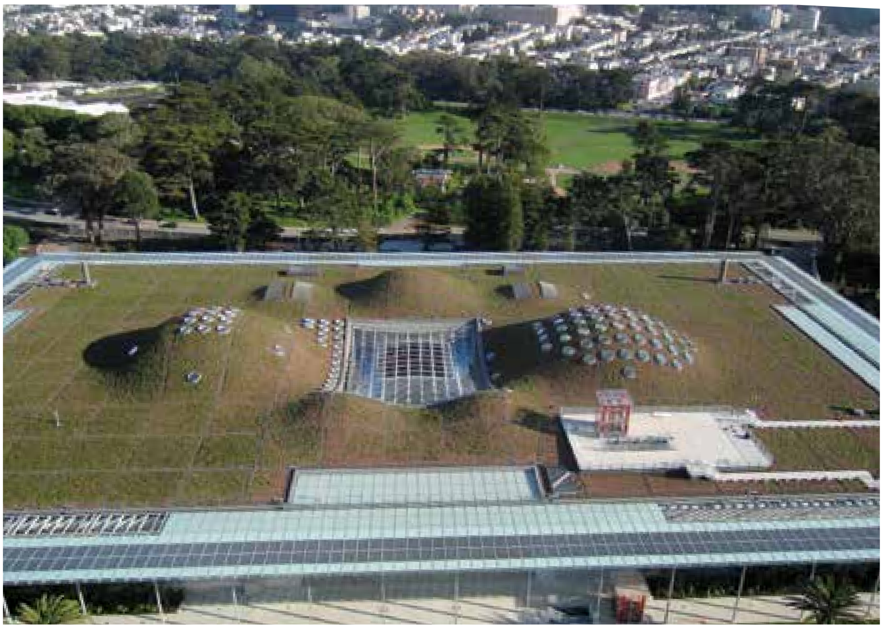


Figure A11.3 California Academy of Sciences
Credit: American Hydrotech, Inc

Further information

www.calacademy.org

www.calacademy.org/academy/building/the_living_roof/

www.greenroofs.com/projects/pview.php?id=509

http://en.wikipedia.org/wiki/California_Academy_of_Sciences

www.swagroup.com/project/california-academy-of-sciences.html

www.hydrotechusa.com/projects/california-academy-sciences

www.asla.org/2009awards/111.html

Case study 2:	Vancouver Convention Centre West, Vancouver, BC, Canada
Year:	2009
Building type:	Municipal/government
Green roof type:	Intensive
System:	Custom
Size:	24 290 m^2 (The complete convention center is 1.2 million feet^2, i.e. 111 500 m^2).
Slope:	56%
Access:	Inaccessible, private (the convention center is owned by BC Pavillion Corporation and includes exhibition space and meeting space for public use)

Designers/manufacturers

- Horticultural and ecological consultation: Paul Kephart, Rana Creek Habitat Restoration
- Architect: Musson Cattell Mackey Partnership; LMN Architects
- Design architect: LMN Architects
- Prime architects: Musson Cattell Mackey Partnership and Downs/ Archambault and Partners
- Plant propagation for living roof: Holland Landscapers.
- Roofing contractor: Flynn Canada Ltd
- Landscape architect: PWL Partnership Landscape Architects Inc.
- Plant supplier: NATS Nursery
- Steep sloped green roof components: American Hydrotech, Inc

Figure A11.4 Vancouver Convention Centre West
Credit (left): Nic Lehoux
Credit (right): LMN Architects

Awards

2013

- AIA National Honor Award for Architecture
- AIA National Honor Award for Regional and Urban Design
- World Architecture News Sustainable Building of the Year Award

2011

- AIA Committee on the Environment Top Ten Award
- AIA National Honor Award, Interior Architecture
- World Architecture News Effectiveness Award

2010

- AIA Northwest and Pacific Region, Honor Award
- AIA Seattle What Makes it Green? Gold Award
- Architect Magazine Annual Design Review, Citation
- British Columbia Wood First Champion
- Green Roofs for Healthy Cities: Green Roof Award of Excellence
- IESNA Illumination Design Award of Merit
- Lumen West Award of Excellence
- Northwest Wall and Ceiling Bureau, Commercial Project of the Year
- Sustainable Architecture and Building Magazine Canadian Green Building Award
- ULI Award for Excellence: The Americas Competition

2009

- AIA Seattle Chapter Honor Award
- Steel Designs Award
- Canadian Consulting Engineer Award of Excellence
- IIDA INawards, Honorable Mention, Design in Public Category
- The Chicago Anthenaum/Green Good Design Award

Figure A11.5 Vancouver Convention Centre West
Credit: LMN Architects

Further information

www.vancouverconventioncentre.com

www.greenroofs.com/projects/pview.php?id=545

http://lmnarchitects.com/work/vancouver_convention_centre_west

www.youtube.com/watch?v=OX0JHdVd27o

Case study 3:	ACROS Fukuoka Prefectural International Hall, Fukuoka, Japan
Year:	1994
Building type:	Commercial
Green roof type:	Intensive
System:	Single-source provider
Size:	97 528 m^2
Slope:	2%
Access:	Accessible, private

Designers/manufacturers

- Architect: Emilio Ambasz, Emilio Ambasz and Associates, Inc
- Associate architect: Nihon Sekkei
- Landscape architect: Nihon Sekkei Takenaka Corporation
- Engineer: Nihon Sekkei Takenaka Corporation
- Engineering consultant: Plantago Corporation
- System manufacturer: Katamura Tekko Company
- Photographer: Hiromi Watanabe

Further information

www.greenroofs.com/projects/pview.php?id=476

www.ecofriend.com/entry/acros-fukuoka-the-serene-green-roof-of-japan/

Figure A11.6 ACROS Fukuoka Prefectural International Hall
Credit: Emilio Ambasz, Architect

Case study 4:	Roppongi Hills Keyakizaka, Tokyo, Japan
Year:	2003
Building type:	Commercial
Green roof type:	Extensive and Intensive, test/research
System:	Custom
Size:	13 000 m^2
Slope:	1%
Access:	Accessible, open to the public

Designers/manufacturers

- Architect: Conran and Partners, JPI, KPF and Mori Building Company
- Landscape architect: Yohji Saski and Dan Pearson

Main features

- Keyakizaka complex rooftop conatins a rice paddy and vegetable plot.
- Sakurazaka roof exhibits public art and street furniture in a garden setting.
- It contains a 4000 m^2 traditional Japanese garden.
- Almost all the buildings have green roofs.
- It showcases the potential for inventive green and vertical urban development.
- Roppongi Hills has 26% of its land area planted with vegetation, with a network of pathways, gardens, and green roofs; soil depths: 30–1200 mm.
- A gardening club has been set up to allow the residents of nearby apartments (Roppongi Sakura-zaka) and other people to do farming (vegetables and rice) and other related activities on the green roofs.

Further information

www.roppongihills.com

www.roppongihills.com/en/green/

www.roppongihills.com/green/rooftop_garden/

www.greenroofs.com/projects/pview.php?id=782

Figure A11.7 Roppongi Hills Keyakizaka
Credit: © Roppongi Hills

Index