Abstract

Sustainable construction, also known as green construction, aims to reduce the environmental impact of a building over its entire lifetime, with regard to its economic, ecological and social aspects, in order to leave behind an intact environment for future generations. The sustainable construction of green roofs plays an important role. Green roofs are widely used in many countries, in recent years a number of projects have been initiated to promote energy efficiency and renewable energy technology. Nowadays, many cities want to be involved in these projects in order to improve their environment. There are many ongoing research projects on the benefits of green roofs, such as improving rainwater management and water quality, the reduction of energy use and air pollution, the improvement of the climate as well as creating new natural habitats for flora and fauna. Green roof insulation can help mitigate the urban heat-island effect, heat loss from building, and also protect against wind effects and atmospheric factors such as storms, hail and UV radiation. One way of increasing the sustainability and energetic efficiency of a building is the installation of a green roof. The purpose of this study is to review the current knowledge concerning the benefits of green roofs.

Keywords: green roof; sustainable construction; ecological benefits; economical benefits; plants

1. Introduction

Sustainable construction is achieved by upholding the principles of environmental protection as well as focusing on the social and economic impact of buildings, in order to leave an intact environment for future generations. The role of green roofs in sustainable development is very important. Green roofs have many benefits that contribute to the quality of the environment on a long-term basis. Furthermore, construction and maintenance of green roofs provide business opportunities.

Before human development started disturbing natural habitats, it was the natural soil and vegetation which constituted parts of a balanced ecosystem that managed precipitation and solar energy effectively (Getter and Rowe, 2006). Nowadays, new cities, neighborhoods, business and administrative buildings are growing across the world. Greenery is disappearing from cities. Impervious surfaces of concrete and asphalt cannot absorb precipitation, the water flows off surfaces and does not infiltrate into the groundwater. In forests, ~95% of rainfall is absorbed, whereas only about 25% is absorbed in cities (Scholz-Barth, 2001). Torrential rainfall disproportionately overwhelms the municipal sewer systems, streams and rivers, causing flooding.

The air becomes less humid and the temperature rises. In cities there is almost no difference between day and night temperatures. According to the USEPA (2003), urban air temperature can be up to 5.6°C warmer than that of the surrounding countryside. In the urban heat island effect situation, even night air temperatures are higher because man-made surfaces absorb heat and radiate it back during the evening hours. In Berlin, temperatures on a clear windless night were 9°C higher than in the countryside (Von Stulpnagel et al., 1990).

These problems could potentially be solved by green roof technology, which offers many advantages. Green roofs capture dust and other pollutants. They help to keep buildings warmer in the winter and cooler in the summer. They can also filter out harmful gases such as carbon dioxide and then release oxygen back into the air. They can absorb up to 60% of rainwater throughout the year. The plants on green roofs can reduce noise inside buildings. A green roof can last up to 2 times longer than a conventional roof, because a green roof will be less expensive and will result in less material in landfill. New studies are showing that green roofs can almost eliminate electromagnetic radiation penetration. Moreover, they even look nice.

2. The history of green roofs

Greenery on green roofs from a historical perspective does not represent a new phenomenon. When people left the caves and mountain gorges, which were protecting them from the elements, they began building the first shelters with roofs from branches and wicker. When they built the first huts, they needed to keep themselves...
warm. Therefore, they sealed the roof with greensward and clay. Airborne seeds covered them with greenery that made for even better insulation. These dwellings can be seen today in every European open-air museum of folk architecture.

The history of green roofs in the world can be divided into two main categories – extensive and intensive. An intensive green roof is what is typically called “roof garden”. It’s traditionally more expensive because the soil medium depths are between 1 and 1.3m to enable the growth of small trees and a wide variety of other plants. The first known historical reference to a roof garden above grade is for the stone temples in the region of Mesopotamia (Werthmann, 2007). Civilizations in Mesopotamia built roof gardens on the landings of Ziggurats, or stepped pyramids, thousands of years ago. The plantings of trees and shrubs softened the climb, provided shade and relief from the heat (Dunnett and Kingsbury, 2008). The most famous green roofs were the Hanging Gardens of Babylon, built by the Persians around the 500 B.C (Weiler and Barth, 2009), one of the Seven Wonders of the Ancient World. In the Middle Ages and the Renaissance, the art of building roof gardens started to develop again, especially in Italy. They were established on the roof of the palace of the Medici - Villa Careggi in Florence and Palazzo Picolomini in Pienza. In Russia, they were built as sign of luxury since the end of the Renaissance period. In the USA, rooftop gardens became popular at the turn of the 20th century.

Extensive green roofs have a thinner profile which makes them lighter and more economical. They were mainly built in Scandinavia, Canada, Iceland, where these roofs are still a traditional element of modern architecture. In the cold Nordic climates, green roofs are preferred for their good thermal insulation properties. They are also used for the opposite reason, to insulate the interior from the outside heat, and they are utilized in some tropical countries, such as Tanzania (Minke, 2001). While the history of roof gardens can be connected with the cities and especially their affluent residents, extensive green roofs are more of a matter of utility (isolation from the surrounding environment) and are found more often in the countryside or in small towns. There is much less information available about the history of extensive green roofs than there is about the history of intensive green roofs. This is probably related to the fact that while intensive roof gardens were urban affairs and also a showcase of social prestige, while extensive green roofs were more of a pragmatic attempt to use nature in the fight against the elements. This may be due to the fact that while the culture of the Mediterranean society was already relatively developed in the antiquity, the northern areas experienced a similar development a while later.

Nowadays, these differences are not as pronounced. These days, the main difference is in their geographical distribution, which is significantly linked to the climate - while in warmer areas (e.g. Mediterranean), there are many houses with roof gardens, in colder regions such as Scandinavia they are logically found very rarely.

The modern history of green roofs

The main pioneers of the modern development of green roofs were German-speaking countries – with Germany at the forefront. In these countries many scientists have been involved in research of new technologies and the possibility of planting green roofs since 1960s. These efforts were mostly successful and the number of green roofs has been growing significantly (Dunnett and Kingsbury, 2008). An interesting and well-known example is the famous Hundertwasser in Vienna. The house, which was completed in 1985, stands in the street Löwengasse. There were a total of 992 tons of soil and 250 trees and shrubs transported to the rooftop of the...
house. Originally it was meant to serve as an accommodation for socially disadvantaged people, but became a tourist attraction and one of the most famous buildings with a green roof in Austria.

The World Exhibition in Paris 1867 was one of the first demonstrations of a planted concrete roof in Western Europe, where visitors could get acquainted with extensive roofs into the mainstream where the showcase of a concrete "nature roof" was displayed (Dunnett and Kingsbury, 2008). The effort to build green roofs due to environmental considerations and to return nature to the life of city dwellers comes only in the 20th century. Perhaps the best known promoter of this idea was the architect Le Corbusier. Le Corbusier is considered one of the first systematic roof greeners. In his famous Five points of new architecture, written in 1930's, roof gardens came second. After a brief explanation of structural details, Le Corbusier concludes with the words: "The roof garden becomes the favorite place in the house and additionally for the town it means that the built-up space lost is regained." (Le Corbusier, 1946).

In the first half of the 20th century, the oversized weight was still an obstacle to the greater development of green roofs, both for structural elements and soil substrates. The development of industrial chemicals and plastics partially resolved this problem after World War II.

In recent years, a lot of architects have begun to design green roofs in many European and non-European countries. In the traditionally environmentally minded countries such as Germany, Austria and Switzerland, there is a large boom of green roofs since the 1960s (Čermáková and Mužíková 2009). Especially in Germany, many specialized companies were set up, which dealt with the research of green roofs, and primarily their implementation, (an example could be ZinCo or Optigrün - Companies based in Stuttgart). In 1989 approximately 100 ha of green roofs were made (Čermáková and Mužíková 2009). The impetus for this was especially strong environmental movement and the effort to return the nature to urban life (Dunnett and Kingsbury, 2008).

Nowadays, the significance and application of green roofs consists in their contribution to the urban landscape. In addition, currently, because of the significant range of construction and the need to protect agricultural land, the use of green roofs is necessary in terms of the economical use of space. The use of a green roof is actually a logical consequence of a lack of space.

3. Why have a green roof

The positive effect of green roofs on air quality may seem irrelevant because of their normal sizes. However, studies have shown that this is not the case, because the improvement of air quality does not require a completely green roof city. There only needs to be a network of them, which can then greatly reduce the negative effects. Green roofs have many features, that are connected with each other, they operate on themselves in various forms, and may have different meanings according to the specific situation. Therefore, green roofs cannot be assessed without interconnection.

In terms of urban design and landscape function, the roof garden is another place where a person can rest and relax. One built-up area can be used multiple times. People do not have to live only on the individual floors of the building, but also on the roof garden and terraces where they may be in contact with plants, animals, the Sun, earth, air or water. In contrast to the tin roof that radiates very harsh light during bright sunlight and the view of
it is unpleasant, sometimes painful, while a view of a green roof is a pleasant and positively affects a person's mood.

3.1. Improving the microclimate

From an ecological perspective, green roofs make a valuable contribution to improving the microclimate. By comparing the green roof with a classical roof with waterproofing or with layer of gravel, green roofs have been proven to be able to equalize the differences of extreme temperatures and reduce the intensity of radiation, but also to enhance the quality of the microclimate in our urban centers. We can see that there is an exchange of thermal energy between the plants and the environment. Green roofs provide shade and remove heat from the air through evapotranspiration, reducing temperatures of the roof's surface and of the surrounding air. On hot summer days, the surface temperature of a green roof can be cooler than the air temperature, whereas the surface of a conventional rooftop can be up to 50°C warmer (Liu and Baskaran, 2003).

The loss of vegetative cover and the increase in building activity in the form of pavements, roads and buildings results in higher urban temperatures than in the suburban and rural areas. As impervious surfaces tend to be heat absorbing, they increase the urban temperature. This specific urban phenomenon termed as the Urban Heat Island Effect (Solecki, et al., 2005), is identified by higher night time temperatures and humidity. Green roofs provide shade and insulation, which results in energy savings and in the mitigation of the urban heat island effect. Media depth, shade from plant material, and transpiration can reduce the solar energy gain by up to 90% compared with non-shaded buildings. Green roofs have reduced indoor temperatures from 3°C to 4°C when outdoor temperatures moved between 25°C and 30°C (Peck et al. 1999).

Graph 1. Average roof surface temperatures for both "greened" and "non-greened" roofs

3.2. Mitigation of air pollution

The plants on the roofs, as well as also other plants produce oxygen and consume carbon dioxide due to photosynthesis. They also filter out dust and dirt in the air. The particles are collected on the surface of leaves and then rain flushes them to the ground. Plants remove gaseous pollutants by absorbing them through the pores in the leaf surface. A German study demonstrated that green roof vegetation can significantly reduce diesel engine air pollution (Liesecke and Borgwardt, 1997). Yok Tan and Sia (2005) found a 37% reduction of sulfur dioxide and a 21% reduction in nitrous acid in the air above a green roof when compared to other air samples taken nearby. Others have estimated that 1 m² of green roof can absorb about 0.2 kg of dust particles and other pollutants per year (Peck, and Kuhn, 2003). Plants also bind heavy metals.

The roof surface without an insulation of gravel and greenery that significantly decreases temperature, can in the summer reach temperatures of 25 °C to 60 °C, in extreme cases even to 80 °C in central Europe. This creates the vertical movement of air above roofs (so-called "thermals"). The roof surface that is 100 m² may have a velocity of 0.5 m/s. Thus, the particles of dust and dirt on the streets and yards, which are blown again into the air over residential areas, create a blanket of dirt and haze. The green roof can significantly reduce air movement, because thermals do not appear above the grassy areas. In the sunlight, the temperature in a grass pillow is consistently lower than the air temperature.
3.3. Rainwater Management

Green roofs also help control rainwater runoff and retention. The increased urbanization of towns and cities has resulted in less green space and more impervious surfaces. Precipitation generally runs off the roof of a building into the gutters and flows into a sewer, but too much rainwater can cause a city’s sewage system to overflow, discharging sewage into streams and rivers. Green roofs can help prevent this by retaining water in the plants and growing medium, thus slowing and reducing the amount of rainwater. The individual layers of a green roof soak stormwater either more or less according to the material and structure until they reach maximum saturation. It is necessary to pay attention to the main vegetation layers of green roofs in general and not to concentrate only on individual segments. During a rain and immediately after it, a large part of the water evaporates and returns to the atmosphere. Green roof can delay runoff between 95 min (Liu, 2003) and 4 h (Moran et al., 2004), compared with the reference roofs for which runoff was nearly instantaneous. Liu (2003) found that the actual precipitation with intensity of 2.8 mm/h was reduced by the use of a green roof to a runoff with intensity of 0.5 mm/h. Also Fioretti (2005), analyzing the effect of a Mediterranean climate on a green roof installed on one of the buildings at the University of Genoa in Italy has observed a delay of water runoff from the roof ranging from 71 min to 306 min. In the course of the same research project carried out in the period September-December 2008, they have obtained results demonstrating a strong dependence of green roof retentiveness on the duration of the dry period preceding the occurrence of precipitation. Whenever the period was shorter than 96 h, the retention capacity was less than 20 %, while for rainfalls separated by less than 12 h, the precipitation water runoff was close to zero.

### Table 1. Average water retention for a transitional roof vs. a green roof.

<table>
<thead>
<tr>
<th>Rainfall Retained %</th>
<th>Standard Roof</th>
<th>Green Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Retention</td>
<td>24%</td>
<td>80%</td>
</tr>
<tr>
<td>Retention at Peak Runoff</td>
<td>26%</td>
<td>74%</td>
</tr>
</tbody>
</table>

3.4. New habitat

The more and the larger urban centers are built up, the less space the animals have to live. Green roofs provide a habitat for wildlife, mainly for plants, microorganisms, insects and birds. Particularly blooming roofs are an attraction not only for butterflies, but also bees and other insects. A biodiversity study of seventeen green roofs in Basel, Switzerland found 78 spider and 254 beetle species. Eighteen percent of those spiders and 11% of the beetles were listed as rare and some were considered to be endangered (Brenneisen, 2003). In Berlin, Darius and Drepper (1984) found grasshoppers, white grubs, beetles, and a high number of mites on 50-year old green roofs, and in Switzerland, nine orchid species and other rare and endangered plant species were found on a 90-year-old green roof (Brenneisen, 2004). In the UK, green roofs have been found to provide habitat for the Black Redstarts, and an endangered bird species (Gedge, 2003). Water surfaces on the roofs also attract many animals, such as birds, for which the water area serves as a drinking fountain and space for cooling. On the roof, which is vegetated, one may purposely set up a location for the cultivation of protected types of plants that have become rare in the natural environment, because the natural environment is becoming progressively more undermined by factors of civilization.

3.5. Extend roof life

One of the major benefits of green roofs is their contribution in prolonging the life of both building insulation and roof surfaces (Weiler and Barth, 2009). Each roof structure, which is in contact with the external environment, is exposed to a large number of factors that damage it and shorten its life. The durability of the materials is determined by the time of exposure. The lifetime of the roof is negatively affected by heat, cold, wind, ozone, ultra-violet radiation or chemical agents. Leaving aside the features of the construction of building, the life of green roofs is basically unlimited with proper establishment. As a result, the roof structure can require less maintenance, saving the owner money in replacement costs over the long-term life of the roofing system. Well-maintained green roofs can more than double the number of years before a roof needs to be replaced compared to a standard roof.
3.6. Noise Reduction

Hard surfaces of urban areas reflect sound and are unable to absorb it. Green roofs absorb sound waves due to the nature of the substrate and the vegetation (Getter and Rowe, 2006). The depth of the green roof assembly acts as an acoustic barrier, the substrate blocks lower sound frequencies while the plants stop the higher frequency, thereby reducing the noise of traffic and airplanes. In a study at the Frankfurt airport, Germany a 10 cm deep green roof has shown to reduce noise levels by 5dB (Dunnett and Kingsbury, 2008). Other research shows that a 12 cm of substrate layer can reduce sound by 40dB (Peck and Kuhn, 2001).

4. Types of green roof

So far, there is no uniform definition that would be universally accepted and used. Lack of uniformity of terminology is often determined by different translations of foreign literature. The most frequently used phrases include: "green roof", "roof garden", "grassy roof", "vegetative roof" or a combination of these phrases.

Table 2. Green roofs are classified according to their depth and maintenance requirement. The following names for different green roofs have been adopted by the construction industry in the UK.

<table>
<thead>
<tr>
<th>Type of green roof</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightweight extensive</td>
<td>Low biodiversity potential, water holding; includes pre-grown vegetation mats Sometimes irrigated; no additional substrate; open substrate</td>
</tr>
<tr>
<td>Super lightweight</td>
<td>Consists of thin (12mm) drainage board, a filter fleece/water retention mat and pre-grown vegetated mat about 25mm in thickness; minimum loadings Sometimes irrigated; practical for some retro-fits Limited vegetation diversity, tendency to dry out</td>
</tr>
<tr>
<td>Extensive</td>
<td>Less than 100mm substrate depth, and not usually irrigated; low maintenance Limited water holding, biodiversity potential Includes pre-grown vegetation mats or substrate</td>
</tr>
<tr>
<td>Semi-intensive</td>
<td>100mm to 200mm substrate depth, moderate maintenance, wider range of plants Sometimes irrigated, rainwater attenuation Supports vegetation; slightly higher maintenance</td>
</tr>
<tr>
<td>Intensive</td>
<td>Over 200mm substrate depth, intensive maintenance requirement Supports vegetation; slightly higher maintenance Sometimes irrigated; lawn or roof garden, amenity Space Water attenuation and some biodiversity can be achieved</td>
</tr>
<tr>
<td>Roof gardens/podium decks</td>
<td>Intensive and well understood Outside the scope of this document</td>
</tr>
<tr>
<td>Biodiverse/wildlife (extensive)</td>
<td>Supports particular species or group of species; natural colonisation often encouraged Limit level of human interaction; focus on biodiversity value</td>
</tr>
</tbody>
</table>
5. Plant selection

Plant selection is very important to the sustainability of the roof. Criteria for selection plant material depend on the growing medium as well as local conditions, available maintenance, desired appearance and plant characteristics such as rate of establishment, longevity and disease and pest resistance and substrate composition and the depth available for planting. Low maintenance, durable and drought resistant plants are used for extensive green roofs, versus a nearly limitless plant selection for intensive green roofs.

Plants for extensive green roofs have to survive intense solar radiation, wind exposure, low nutrient supply, limited root area and need to be drought and frost resistant. For this type of roofs, we can find a narrow range of species limited to grasses, herbs, mosses, and drought tolerant succulents, a succulent plant known for its tolerance to extreme conditions. The plants have to be able to store high amounts of water in the leaves to recover easily from periods of drought. Successful candidates for extensive green roofs are Sedum, Delosperma, Euphorbia and Sempervivum because they tolerate drought conditions and also have strong persistent qualities. In Germany, Liesecke (1990) tested Sedum and found that it could survive more than 100 days without water. Extensive green roofs generally require less maintenance and are generally less expensive to install than intensive green roofs.

Intensive green roofs utilize a wide variety of plant species that may include perennials, herbs, grasses, shrubs and trees. It is important to avoid plants that are too aggressive, which could then displace the other species. Intensive green roofs usually have a higher requirement for water, labor and other resources than extensive green roofs.

6. Installation

Before an initiation of a green roof, one needs to consider the slope, the structural loading capacity, and the existing roof materials, as well as the nature of any drainage systems, waterproofing, and the electrical and water supply that is in place. He should also know who will have access to it, who will do maintenance, and what kind of sun and wind exposure the roof gets.

When the issue of building the structure is resolved, it is necessary to choose a method for installing the plant material. Several methods exist for installing plant material in green roof systems. Vegetation may be planted directly on the roof as seed sowing, cuttings, root ball plants and pre-cultivated vegetation mats in the field at ground level as blankets or modular trays and then transported onto the roof. Care must be taken to avoid damaging the waterproofing membrane during installation.

The best time of year to plant a green roof is in early spring and late summer. For planting during the summer it is important to supply enough water to compensate for periods of low precipitation. One day of hot dry sun with temperatures of more than 30°C could destroy the entire planting. In late autumn cold days may lead to damage of the plants due to frost. Full coverage of extensive roofs should be completed within one year.

7. Maintenance

It is important to provide maintenance to ensure the long term aesthetic quality and the functionality of a green roof. Green roof plants require regular care and attention including irrigation, weeding, fertilizing, pruning and replanting. Some maintenance procedures should be planned immediately after damaging events such as storms or floods, while others can be planned according to seasonal events such as the germination period, season for certain unwanted and invasive species and in the fall after leaf fall. The frequency of maintenance depends on the type of vegetation and includes the inspection of the roof edges, penetration of roots, the control of irrigation and drainage facilities, mowing, the removal of undesirable vegetation or watering and fertilizing. Maintenance of extensive green roofs is usually carried out once or twice a year, unlike intensive roofs which require a more frequent maintenance.

The drainage of a green roof is the same as for a standard roof through gutter located on the roof surface or on its edge. In normal conditions, approximately 300 m² of green roofs can be channelled into a gutter of DN 100.

In the initial phase after sowing or planting, plants should be watered immediately and then watered frequently for the first few weeks unless ample rainfall occurs. Therefore, in the project it is necessary to design enough large water supply connections on the roof or in its vicinity. After the establishment period during the first year, watering may not be necessary depending on the local environment and the plant species chosen. The amount of water required depends on the plant species. In general, extensive roofs should not require irrigation. For an intensive green roof, there is a possibility of water retention in the drainage layer, ideally with automatic irrigation. This will significantly reduce costs and optimize irrigation as it utilizes the stored rainwater first.
8. Costs

The cost of a green roof depends on the type and other factors such as the depth of growing medium, selected plants, size of installation, use of irrigation. Intensive green roofs usually require a greater investment. The estimated costs of installing a green roof with waterproof membranes begin at $10 per square foot for extensive roofing, and $25 per square foot for intensive roofs (Riggs, 2013). Most homes are not prepared for a living roof, and redoing the structure can drive up the cost even further.

Researchers and communities are beginning to perform detailed, full life-cycle analyses to determine the net benefits of green roofs. A study done at the University of Michigan compared the expected costs of conventional roofs with the cost of a 21,000-square-foot (1,950 m$^2$) of a green roof and all its benefits, such as stormwater management and improved public health from the absorption of nitrogen oxides. The green roof would cost $464,000 to install versus $335,000 for a conventional roof in 2006 dollars. However, over its lifetime, the green roof would save about $200,000. Nearly two-thirds of these savings would come from reduced energy needs for the building with the green roof. (Clark and Adriaens and Talbot, 2008)

9. Conclusion

A few years ago, the concept of plants on the roof was viewed with skepticism but this way of perception has been gradually changing and green roofs are widely used today. Green roofs have great potential, due to the development of urban space. Every day buildings and roads swallow hundreds of hectares of green areas. Greenery in densely populated cities is precious and prices of land reach breathtaking sums. The situation has taken a turn for the worse, especially in urban centers; the noise, heat, dust, street traffic, the view of gray building and the loss of natural habitats all significantly contribute to the feeling of stress. These ill effects associated with the rapid expansion of a built-over environment may be minimized by installation of green roofs. Green roofs are one of the few passive techniques that accomplish multiple goals simultaneously. Apart from the economic benefits as its energy cost reduction, green roofs also provide social, environmental and aesthetic values. In addition, the construction and maintenance of green roofs provide business opportunities for construction companies, nurseries, landscape contractors, irrigation specialists, and other green industry members while addressing the issues of environmental stewardship.

Acknowledgement

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS13/116/OHK1/2T/11.

References


