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ROTES
ENHANCING THE RELEVANCE OF VOCATIONAL TRAINING FOR ROOFERS

MODULE 2

Sustainable roofing methods

OPEN EDUCATIONAL RESOURCES

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1. Introductory

1.1. Introduction to green roof systems and environmental benefits

- Understand the basic concepts of green roofs and analyse the environmental benefit of energy systems and installations, as well as their sustainability.
- Determine the environmental parameters for improvement with green roofs (e.g. air quality, temperature).
- Be aware of the importance of the presence of green spaces in cities.

1.2. Green roof energy savings in buildings

- Analyse the impact of the green roof on the energy savings of a building.
- Calculate energetic parameters through a methodology.
- Become familiar with the benefits for the user, both environmental and economic.
- To be aware of energy control and monitoring equipment.

1.3. Green roofs as a nature-based solution in urban areas

- Understand the benefits for the health and well-being of the population, as well as the level of comfort for the users.
- Be aware of the advantages of nature-based passive solutions and the contribution to the SDGs in densely populated areas.
- Calculation of the effect of green roofs on ambient temperature.
- Application of environmental technologies and sustainability.
- Green roofs as a nature-based solution to reduce the carbon footprint and the heat island effect.

1.4. Green roof waterproofing, drainage & recovery

- Study the water management system used on green roofs.
- Analyse hydraulic circuits to properly deviate the water.
- Determine the adequate materials to reduce the risk of flooding.
- Analyse the possible uses of the water recovered through the green roof.

1.5. Integration of renewable systems in green roofs

- Assess the energy efficiency of a green roof and the potential of integration of renewable resources on it.
- Evaluate the introduction of different renewable technologies on green roofs.
- Study the economic and energy benefits brought to the system.
- Identify the proper disposition for PV panels to ensure.

2. Lecture notes

2.1. Introduction to green roof systems and environmental benefits

1. What is a green roof and what does it entail?

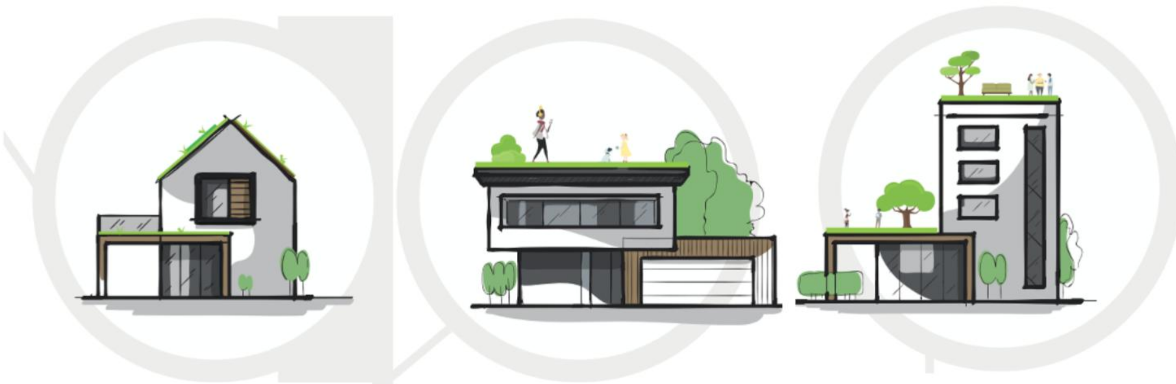
Green roofs are increasingly present in many buildings and the color green is being seen on rooftops in cities, as green roofs present an innovative ecological proposal to the traditional architectural approach. As will be addressed in this unit, a well-planned green roof represents a sustainable urban planning with a multitude of benefits, both for the building and the urban environment. This urban development method aims to minimise damage to the environment while preserving as much of our resources as possible and transitioning to renewable resources wherever possible. Hence, green roofs are growing in popularity, as they have proven to be a cost-effective strategy for creating more livable and sustainable cities.

A green roof is a constructive installation that has a vegetation cover on top of soil or substrate and is specially conceived to obtain **environmental benefits**. The roof contains four main components- a membrane to protect the structure of the roof, a drainage layer, growing medium and finally the vegetation.

2. Green roof systems

Green roofs can also be categorized into two types: intensive and extensive. Their main differences and benefits are explained below.

- **Intensive green roofs** (also referred to as roof gardens or terraces) are composed of lush vegetation and are based on a relatively nutrient rich and deep substrate. They can sustain large plants and even conventional lawns; therefore, intensive roofs generally require relatively high levels of maintenance, regular irrigation and applications of fertiliser, and can be of considerable weight. Intensive roofs also tend to be more expensive than extensive roofs because of the need for a more structurally sound building to support the load generated. The green areas of intensive roofs can add great value to buildings, with better views. Therefore, this type of green roof implies great environmental benefits (biodiversity, reduction of the heat island effect, improvement of air quality, etc.) but also other social benefits due to its accessibility (creation of vegetable gardens, better comfort of residents and quality of life, etc.).
- **Extensive green roofs** are normally characterized by a shallow growing medium and self-sustaining, low maintenance planting that covers the entire roof area. Given that they have a relatively low weight (compared to intensive green roofs), extensive roofs can be retrofitted to many existing buildings (Block et al., 2012) and usually receive no irrigation or fertilization (although this may be required initially until plants become established). The benefits of this type of green roof are environmental (water management, reduction of the heat island effect in urban areas, reduction of the building's energy consumption, etc.) but can also benefit the building in which it is located (lower energy costs, lower maintenance costs than other systems, etc.).
- Between intensive and extensive green roofs, there is a variety of intermediate types typically referred to as **semi or simple-intensive.** Suitable for visible and accessible roofs, they require green and flowering plants throughout the year.



Extensive green roof **Semi-Intensive green roof** **Intensive green roof**

Figure 1. Types of green roofs. Image: green Infrastructure Guide

3. Parameters for improvement with green roofs

The integration of green roofs into the urban landscape can bring certain environmental benefits. However, there are also economic and cultural/social benefits. Here are the main benefits of green roofs which will be detailed in the next unit *Green roofs as a nature-based solution in urban areas.*

ENVIRONMENTAL	- Improvement of **air quality** - Improvement of **stormwater management** - Reduction of **energy consumption** - Reduction of the **urban heat island effect** - Promotes **biodiversity**
ECONOMIC	- Appreciation of the **land value** - **Employment** enhancement - Reduction of **energy consumption** - Extends **life span** of roof - **Economic development**
SOCIAL/CULTURAL	- Reduction of **ambient noise** - Improvement of the **aesthetics of a building** - Generation of a greater sense of **well-being**

Table 1. Overview of the benefits with green roofs

2.2. Green roof energy savings in buildings

1. Energy benefits of green roofs

The use of green roofs to improve energy efficiency is an energy saving technique that has been widely corroborated by numerous papers and research. Green roofs are able to improve the energy efficiency of a building and reduce its energy consumption through various phenomena.

2. Green roof phenomena for energy saving in buildings

a. Vegetation properties

The first cause is due to different characteristics of plants, such as their consumption of sunlight energy due to the performance of different physiological processes such as photosynthesis and evapotranspiration, as well as the generation of shadows on our roof and the reflectivity of the plants.

The **consumption of solar energy by the vegetation** and the blocking of part of the incident radiation on the roof reduces the flow of energy into the building. This effect results in a decrease of the temperature inside the building, especially on the floors closest to the roof.

In addition, the **process of evapotranspiration** also causes green roofs cool down through latent heat loss, lowering the temperature of the air above the roof and the temperature of the substrate. Evapotranspiration is primarily known as the combination of two processes evaporation from the soil and from the surface covered by plants and transpiration from plant leaves. This can be contrasted in warm conditions, in the case of the bare roof or no green roof. The heat accumulated during the day continues to enter the building during the night, radiating the stored heat and increasing the ambient temperature. However, measuring the air temperature at various heights above the green roof shows that, after sunset, the ambient air temperature above the vegetation is significantly reduced and continues to cool the ambient air throughout the night.

Another cause is the **reflection of light on an exposed surface**. In this respect, it has been found that in summer the exposed surface of a black roof can reach 80 ◦C while on a green roof it is around 27 ◦C. Green roofs are therefore cooled by enhancing the reflectivity of incident solar radiation. Another cause is related to the radiation albedo, known as the ratio of total reflected to incident electromagnetic radiation. Green roofs cool as effectively as the brightest white roofs, with an equivalent albedo of 0.7-0.85, compared to the 0.1-0.2 typical of a bitumen, tar or gravel roof.

These phenomena depend directly on the type of vegetation used, with larger plants with wider leaves generating more shade and consuming more energy, and plants with more green parts reflecting more light. The vegetation that reduces energy consumption the least is grass, and the plants with the highest proven efficiency are leafy shrubs and ferns.

b. Thermal insulation

A main objective of green roofs is to increase the **thermal insulation**, which in other words means to decrease the thermal transmittance of the roof. This is the fourth way to save energy: improving the thermal insulation of the building.

In order to understand the effect of the insulation on energy savings, it is important to learn about the different layers that make up a green roof. Roofs are made up of several layers and components that can vary from installation to installation (as discussed in the previous unit):

1. **Thermal insulation**: it is always advisable to have a thermal insulation that ensures the thermal bridge break in the event of high percentages of humidity in the substrate.
2. **Waterproof membrane**: Protects the building from water leaks and is always necessary.
3. **Drainage or water storage material:** It is advisable to provide a water storage or evacuation space to remove excess moisture from the substrate and thus improve the insulation level of the roof.
4. **Filter layer:** Allows the extraction of water from the substrate.
5. **Root barrier:** Prevents roots from damaging or penetrating the other layers.
6. **Substrate:** Provides consistency to the canopy and serves as support and food for the plants.
7. **Vegetation:** Includes the different plant species planted in the roof.

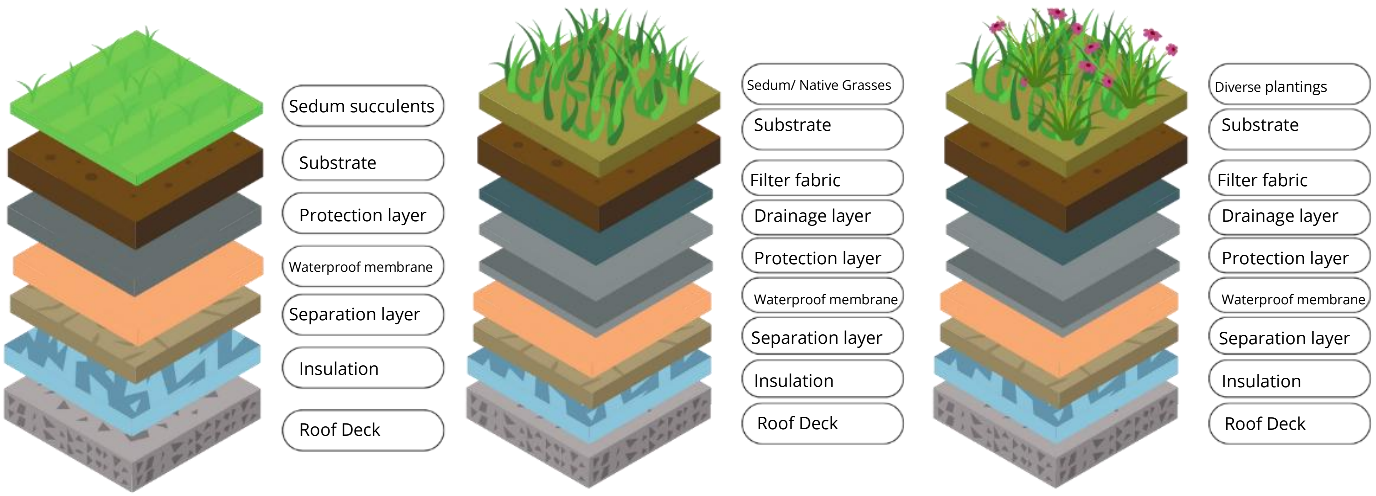


Figure 2: Intensive, semi-intensive and extensive types

Of these layers, the ones that have the greatest effect on the thermal insulation of the roof are the **insulation layer** itself, the **drainage or water storage** system and the **substrate**.

The **substrate** can vary the transmittance of the roof depending on two factors, the bulk density of the soil and its humidity content. On the one hand, a low bulk density leads to a high thermal diffusivity which results in a low thermal transmittance. On the other hand, a high percentage of humidity increases the thermal transmittance of the floor. In fact, the possibility that rainfall or irrigation may increase the humidity of the substrate is the reason why it is advisable to have a thermal insulation and a drainage mechanism.

Some parameters of importance to understand the phenomena of energy savings in green roofs are described below:

- **Heat transfer *Q*.** Only heat transmitted by conduction and convection are considered. Conduction is the transfer of heat between substances that are in direct contact with each other. Convection is the heat transfer by the macroscopic movement of a fluid.
- **Thermal transmittance *U*.** Physical property of materials that measures the amount of energy an element passes through in a unit of time.The lower the U value, the better the housing will have.
- **Convective heat transfer coefficient *h*.** Heat transfer rate between a solid surface and a fluid per unit area per unit temperature difference. It depends on the physical properties of the fluid and the physical situation.
- **Thermal conductivity K.** Ability to transmit heat measured through the magnitude known as thermal conductivity coefficient. The lower the value of K, the better the insulation of the material.
- **Thermal diffusivity α.** It is the rate at which heat diffuses through a material, so the higher the conductivity, the higher the diffusivity.

By relating the above parameters, it is possible to obtain the following formulas that regulate the behavior of the green roof for heat transmission and, therefore, influence energy savings.

(1) The heat transfer (W) through the walls, it can be expressed with "**Fourier's Law**":

$$Q = U \cdot A \cdot dT$$

- $A = Heat\ transfer\ area\ (m^2))$
- $dT = T_1 - T_2$ = *temperature gradient - difference over the material (°C, °F)*

(2) Heat transfer coefficient per unit area or transmittance $\left(\frac{W}{m^2 * K}\right)$

$$U = \frac{K}{th} + h_i$$

- $K = Thermal\ conductivity \left(\frac{w}{m * k}\right)$
- $th =$ *material thickness* (m)
- $h_i =$ *convective heat transfer coefficient* $\left(\frac{w}{m^2 * k}\right)$

(3) Thermal conductivity of the material $\left(\frac{w}{m * k}\right)$

$$K = \alpha * \rho * Cp$$

- $\alpha = Thermal\ diffusivity \left(\frac{m^2}{s}\right)$
- $Cp = Specific\ heat \left(\frac{J}{K * Kg}\right)$
- $\rho = Bulk\ density \left(\frac{Kg}{m^3}\right)$

An example using these factors was given for modelling a multi-storey residential building in Madrid (Spain) with the ESP-r (Environmental Systems Performance-research) thermal simulation program. ESP-r used the finite element approach to model heat, air, moisture and electrical energy flows. In this case, the thermal performance of a building without a green roof, with a green roof and with a green roof capable of storing water, both covering the exposed roof surface, was compared. The U-value of the roof was reduced from 0.59 to 0.42 with a green roof and to 0.38 for the green roof with water storage.

c. Thermal mass

The last way to reduce energy consumption is to increase the thermal mass of the building, which is directly dependent on the mass of the different layers, especially the substrate and vegetation, and the specific heat of each layer. A high thermal mass helps to stabilise building temperatures, thus reducing peak demand.

3. Energy savings on green roofs

Ultimately, the existence of a green roof helps regulate the temperature of the roof and the interior of the building, thereby reducing the amount of energy used for cooling and, therefore, the associated costs. From an energy point of view, green roofs can be considered as passive elements that, when installed on the roof of a building, modify the energy transfer between the roof of the building and the exterior, increasing the albedo of the roof, increasing the thermal inertia of the roof and attenuating the temperature values supported by the roof of the building.

Total energy savings vary greatly depending on roof design, climate and building height. Overall, the highest energy saving potential corresponds to those cases where the green roof is installed on poorly insulated buildings. These savings are around 1-15% of annual energy consumption due to reduced use of cooling and heating systems and milder indoor temperatures, although in a study carried out in the Mediterranean climate (Greece) annual savings of up to 44% were obtained for a poorly insulated roof.

4. Conclusions

Green roofs are an excellent method of saving energy and improving energy efficiency as they improve the thermal comfort of buildings, improve their thermal envelope and protect them from radiation. These positive effects depend largely on the choice of vegetation, the existence of a specific insulation layer and the existence of a drainage or water storage system.

2.3. Green roofs as a nature-based solution in urban areas

1. Relevance of Nature-Based Solutions in Urban Areas

Cities are full of hard, impervious surfaces that have replaced natural terrain so that built-up areas have less and less soil available for planting vegetation and therefore have lost the benefits that plants provide in natural areas. Climate change is affecting ecosystems with great intensity through heat waves, torrential rains or loss of biodiversity and urban areas seem particularly exposed.

The International Union for Conservation of Nature (IUCN) defines nature-based solutions (also referred to as NBS) as "actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits. In this sense, green roofs are a technology that can help mitigate some of the negative effects of hard urban landscaping by reintroducing a natural landscape into urban city environments. In addition, they can bring numerous social, environmental and economic benefits to an urban area.

2. Environmental benefits of green roofs

- **Stormwater management.** Some studies classify green roofs as one of the best ways to address wet weather flows in urban areas with high-density development. Green roofs can be part of a site-level stormwater management plan. They can reduce the rate of runoff by 65% and extend the amount of time it takes for water to leave a site by up to 3 hours. In addition, the ability of green roofs to buffer acid rain can be a significant advantage in areas where acid rain is frequent. Some green roofs are equipped to harvest rainwater as an alternative water supply for later use. Rainwater captured from green roofs is usually used for irrigation, flushing toilets, and for other non-potable purposes.

- **Biodiversity and habitat.** Green roofs can provide new habitats for plants and animals in urban areas, increasing local biodiversity. The most important factors for promoting biodiversity in a green roof are the type of vegetation, the depth of the growing medium, and variation in plant height and spacing. It can be highlighted that intensive roofs typically support a greater diversity of rare bird species than extensive roofs. Studies suggest that the depth, topography, vegetation composition and age of the green cover, as well as the local landscape, may affect the ability of the cover to enhance biodiversity. Green roofs attract pollinators and provide shelter, food and habitat for many other species, especially birds.

This contributes to the ecological balance of the city, preventing the appearance of pests and protecting various animal species.

- **Urban Heat Island (UHI) effect.** This effect is common in cities where natural landscapes, which absorb a significant portion of solar radiation to create steam, have been replaced with non-reflective surfaces that absorb most of the solar radiation and re-radiate back into the environment as heat. Heat islands increase energy consumption and can cause heat-related illness and mortality. Evaporation and transpiration by plants play a key role in cooling green roofs so that plants and green roofs can help mitigate the UHI effect common to the urban environment.

- **Energy consumption of buildings.** An energy conservation measure such as green roofs can help meet the 2030 targets for public, residential and other commercial buildings to reduce their energy consumption. Green roofs can reduce the amount of heating from solar radiation a building experiences in the summer, and can insulate buildings, providing heat retention in the winter. Because green roofs absorb sunlight, provide shading, promote evapotranspiration, and deliver insulation benefits, they help maintain indoor temperatures. This helps lower the dependence on air conditioners and heating systems. The exact amount of energy saved depends on the climate, the type of roof and building, the height of the building and its neighbors, the amount of moisture on a roof, the variability of temperature changes throughout the day, and seasonal variations in temperature.

- **Air quality.** Although the amount of carbon required to create and install a green roof is typically higher than the amount of carbon it can absorb, when energy savings are factored in, a green roof can be a net carbon sink. As such, a green roof could be used as a carbon sink in different businesses or urban buildings. In addition, the vegetation on green roofs can absorb air pollutants and particulates, serving as a purifier for both indoor and outdoor air.

- **Creates a fire-resistant barrier.** Plants naturally contain a large amount of moisture. With a ground cover a natural fire-resistant layer can be created in a house or office building**.**

3. Social benefits of green roofs

- **Urban Agriculture**. Depending on structural loads and accessibility, agriculture on green roofs could offer an outlet to educate urban residents about food production and seasonal variety, and may boost local gardening efforts. Rooftop farming could also help generate jobs.

- **Acoustic Isolation.** Green roofs reduce noise better than traditional and concrete roofs. When used on buildings without sufficient roof insulation, green roofs can improve noise reduction in the upper levels, especially in areas with heavy motorized or air traffic. The effect is especially pronounced in densely populated areas where outside noise is greater.

- **Aesthetics and quality of life.** Green roofs create an attractive space for tenants and occupants of neighboring buildings. This improves quality of life by reducing stress and improving worker productivity. Green roofs can also provide a recreational space with a greater sense of security.

4. Economic benefits of green roofs

- **Job Generation.** Green roofs can provide green job generation through the production, installation and maintenance of green roofs.

- **Economic development.** Green roofs can provide investment benefits for building developers and owners and provide marketing opportunities to the building.

- **Roof longevity.** A properly installed green roof should only be replaced if the membrane underneath has aged to the point of needing repairs. Some studies suggest that the average life expectancy of a green roof is 40 years, compared to 17 years for a conventional roof.

5. Tools for modeling the effect of green roofs in urban areas

Due to the diversity of factors that influence the heat transfer process of a green roof (as seen in the previous chapter), the benefits obtained at the urban level, such as the impact on the Heat Island Effect or air quality, must be simulated with specific tools. Some of these tools include:

- **Canopy models coupled to building energy models (CM-BEM**) are now widely used worldwide, and are composed of a canopy model (CM) and a building energy model (BEM). This has been applied to the evaluation of urban heat island countermeasures, energy savings, estimation of electricity demand for air conditioning, or heat-related disease damage.

- **Software ENVI-met**. This software allows to analyze the climatic interaction between buildings, surfaces and plants on a very small scale. It has a variety of applications within the field of building design, urban development, energy analysis, as well as solutions for climate change adaptation.

- **Trnsys**, it is a simulation program of transitional systems with a modular structure. TRNSYS has become a reference software for researchers and engineers around the world. The main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells.

2.4. Green roof waterproofing, drainage & recovery

1. Current problems in cities

As cities grow, natural ground cover is replaced by artificial surfaces such as asphalt and concrete, which prevent rainwater from being absorbed by the ground.

In a typical urban area, rain falling on paved or built-up surfaces flows rapidly into the nearest mass of water. This excess rainfall runoff can cause numerous environmental problems, such as damaging water quality by carrying urban pollutants into water bodies, eroding riverbanks, or causing flooding. In cities that built their sewer systems before 1930, their storm drains often flow into those that carry sewage from buildings to water treatment plants. This can be a problem because when the volume of stormwater is very large, it can cause combined sewer overflows and release raw sewage into rivers and lakes. Especially in high-density urban areas, green roofs can be the most practical way to deal with sewer overflows.

2. Effects of green roofs on stormwater management

Green roofs help regulate stormwater and mitigate the effects of pollutant rainfall such as acid rain. Thus, the effects of green roofs are to decrease runoff and reduce pollutants from rainfall.

a. Reducing runoff

A green cover affects runoff in two main ways:

1. **Increasing the amount of water** that remains in the cover after a storm.
2. **Reducing the rate at which water flows** from the roof to the storm drain.

- On the one hand, the **retention of stormwater** helps protect sewers and wastewater treatment plants from overflowing or saturation. Green roofs have been shown to retain between 38% and 54% of rainfall with a soil depth of 10 cm. The ability of a green roof to absorb and retain rainwater depends on several factors, including the drainage layer, the growing medium, the plants (or vegetation), the slope of the roof, the season and climate and the roof size.
- On the other hand, in terms of **drainage systems**:
    - **Multi-layer systems** are the most installed in North America. In these systems, the growing medium covers a separate drainage layer that is usually sand or gravel or covered with a filter fabric, or a layer of synthetic geocomposite of plastic, rigid filaments, or the like. Specifically, Geocomposites are multilayer materials made from a combination of synthetic polymers to serve a specific function, such as increasing the waterproofing of a vegetative cover or promoting drainage. Many geocomposite layers can also serve as a reservoir and are designed to store water in addition to draining.
    - **Granular drainage layers**, such as sand and gravel, tend to increase retention time and delay peak runoff. These drainage layers help plants develop their roots better, but they are heavier and store less water than geocomposites.

- Finally, the **depth of the substrate** also affects the amount of moisture the substrate can retain, as does the choice of plants used. Choosing plants with higher evapotranspiration rates increases the rainwater absorption of a vegetative cover, however, these plants often require a deeper growing medium and may also require a supplemental irrigation system, which must be managed carefully, as overwatering can reduce the roof's ability to retain rainwater. Turning to substrate depth, it is worth noting that total retained moisture increases at a slower rate than media depth.

Green roofs can be a key element of a stormwater management plan, reducing peak flows by up to 65% and increasing the time it takes for water to flow from one location to the sewer by up to three hours, depending on the size of the roof and the distance the water has to travel. For a green roof to provide these services, it must be at least 5 cm thick. Unlike most other structural good management practices, green roofs reduce runoff rates on both large and small surfaces. The plants, growing medium, and other materials on a green roof are what allow it to absorb stormwater.

b. Reducing pollution

With respect to the other effect, reduction of water pollution, the advantages of these systems are:

1. **The buffering** of the effects **of acid rain**
2. **The filtration of various pollutants** contained in the rain.

This is due to the fact that plants are able to absorb and incorporate into their tissues various polluting substances as well as acting as a protective layer against the buildings where they are located. However, special attention must be paid to the nutrients fed to the plants, since the phosphorous and nitrates added to the fertilizers used can be washed away by rainfall and contaminate nearby bodies of water.

3. Rainwater recovery

There are rainwater harvesting systems on green roofs, which collect all the water that is not consumed by the plants and guide it to a tank or cistern. The plants and the mixture of mineral and plant substrate together with the geotextile materials filter up to 90% of the pollutants from the rainwater. This rainwater harvesting system is capable of recovering and filtering up to 60% of the rainwater.

The rainwater harvesting system can be installed in all types of buildings (houses, factories or companies) to achieve a sustainable benefit (economic, social and environmental) and have a positive and cyclical impact on the culture of environmental care. In addition, it is also possible to use the stored water for the irrigation of the roof itself.

There have also been cases, mainly for intensive green roofs, where dams have been created for amphibians and other animal species that also use the stored water. In these systems, a recirculation pump is used to renew the water.

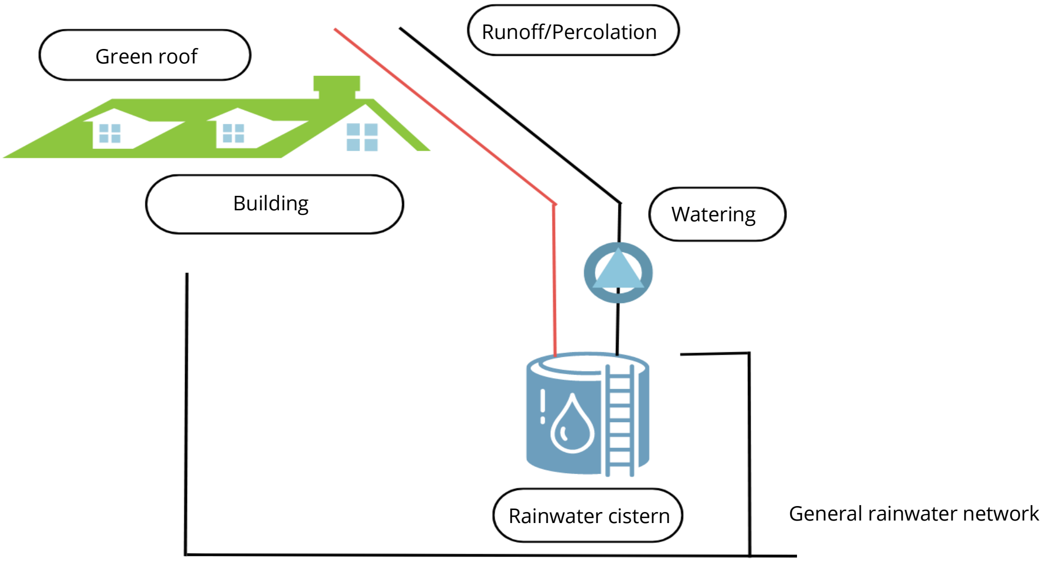


Figure 3: Scheme for reuse of rainwater for irrigation of green roofs

2.5. Integration of renewable systems in green roofs

a) Integrating renewable energy with green roofs

As we have seen in the previous units, the construction of green roofs has numerous environmental, economic and social benefits. However, some studies have shown that using **green roofs together with solar PV** arrays brings the benefits of green roofs (energy savings, storm- water management, biodiversity improvement) together with the benefits of solar PV panels (on-site energy generation, carbon-free energy generation, reduction of grid-sourced energy use) and synergies between both systems (pump drive for water renewal in ponds). Other potential integrations have been explored the use of wind energy or biomass.

In the case of **wind energy**, using vertical axis wind turbines at edges and corners of green roofs could take advantage of turbulent wind without regard to orientation, while also reducing wind uplift forces and allowing for a more moderate rooftop microclimate.

In addition, there are also possibilities to grow plants for **biomass** on or within building envelopes, which uses an innovative bioreactor facade with algae growing within. The algae can be harvested and turned into biogas, which generates electricity. Similarly, the residual biomass of green roof or wall plants can be harvested to generate energy. If biomass production is a goal, plants that produce more biomass than typical green roof plants can be selected if water, nutrients, and structural loading capacity are available. Some of the ideal species for the incorporation of biomass in vegetative covers are herbaceous plants such as carinata or rapeseed, which are fast-growing.

b) Benefits of integrating PV panels with green roofs

Currently, the most widely used renewable energy is PV panels. The synergies between green roofs and PV panels can be far-reaching:

- **Better use of space** that captures the benefits of both technologies.
- **Increased efficiency of solar PV** panels due to reduced ambient temperature from evapotranspiration.
- **On-site generation** of renewable energy, which can also be used to power irrigation equipment for the green roof.
- **Increased revenue/savings** (from generated energy) can offset the additional costs of a green roof.
- Solar **PV panels protect the plants** and growing media from direct exposure to sunlight and wind, reducing drying and excessive evapotranspiration, which enhances plant growth and creates microhabitats that encourages species variety.
- **Racking and support systems for solar PV panels** can be designed so that the green roof layers act as tiles, thereby saving the need for roof penetrations or concrete pavers.
- Increased membrane life due to the protection of green roofs mean solar **PV panels must be moved for re-roofing less often.**

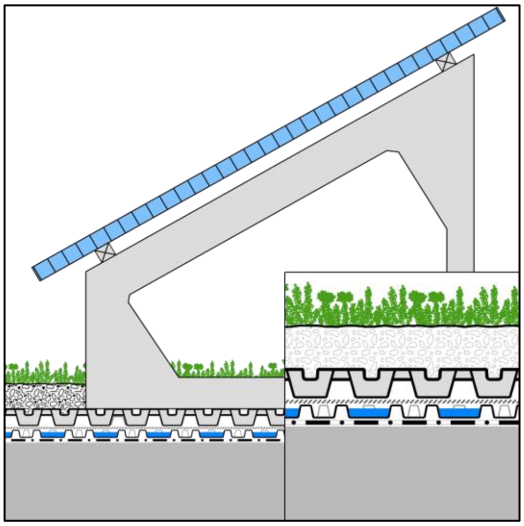


Figure 4: Integration of panels on green roofs. Image: Zinco Cubiertas Ecologicas

c) How to know the orientation of the PV panels on the green roof?

Using the free online PVGIS software, the photovoltaic energy produced by any photovoltaic installation in Europe can be calculated. It also has a database of solar radiation since 2005, so it is also possible to see very well the evolution and stability over the years and thus make more realistic generation calculations. There are also other databases in case the PV installation is not located in Europe.

With this software it is possible to select the concrete layout of the panels, so that it can help to estimate their location on the green roof. The location of the PV system must first be entered in the PVGIS software. To obtain the optimum values for the layout of the solar panels, different options can be selected to obtain the optimum tilt and azimuth. To do this, you must select:

- **Inclination:** the inclination of the panels with respect to the horizontal plane must be entered. PVGIS also gives the option, by ticking the "Optimise tilt" box, to indicate the best tilt for the location of the photovoltaic system being calculated.
- **Azimuth (orientation):** This is the deviation, in degrees, from south. That is, -90º would be East orientation, 0º would be South orientation, and 90º would be West orientation. PVGIS also gives the option of checking the "Optimise Tilt and Azimuth" box to indicate the optimum values**.**

Also, there are three different types for PV system:

- **Performance of grid-connected PV systems.** This tool makes it possible to estimate the average monthly and yearly energy production of a PV system connected to the electricity grid, without battery storage. The calculation takes into account the solar radiation, temperature, wind speed and type of PV module.
- **Performance of tracking PV.** PV modules can be placed on mountings that move the PV modules to allow them to follow (track) the movement of the sun in the sky. In this way we can increase the amount of sunlight arriving at the PV modules. This movement can be made in several different ways: vertical axis, Inclined axis and two-axis tracker.
- **Performance of off-grid PV systems.** This part of PVGIS calculates the performance of PV systems that are not connected to the electricity grid but instead rely on battery storage to supply energy when the sun is not shining.

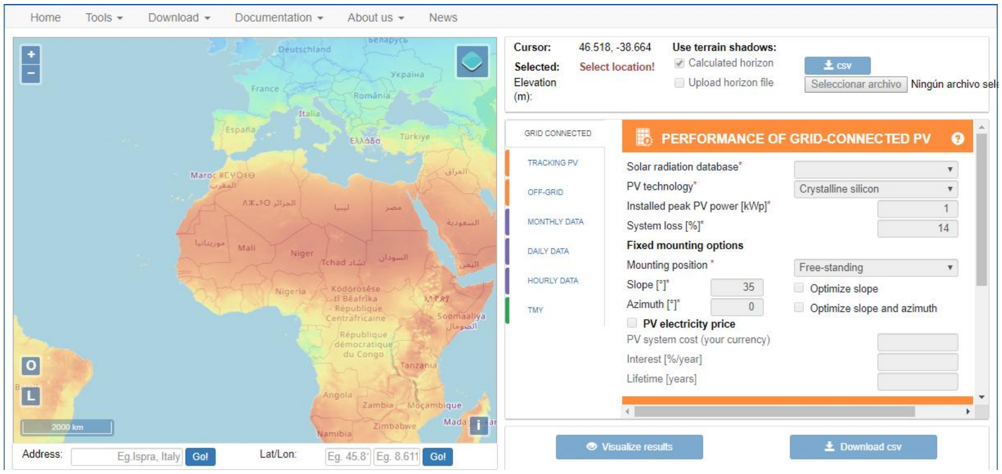


Figure 5. Screenshot of PVGIS to calculate the layout of the solar panels.

d) Research Highlights:

- The comparison of two solar cladded roofs in Sydney, Australia, one bare beneath its panels and the other adorned with native grasses and plants, has found the panels on the green roof were, on average, 3.63% more efficient, producing an average daily output 13% greater than the conventional roof. The improvements are believed to stem from the lower temperatures on the green roof, thanks to its plants – which also provided additional benefits (UTS - University of Technology Sydney, 2021)
- Solar PV panels are less efficient as ambient temperatures rise. High rooftop temperatures increase the conductivity of a crystalline silicon panel's semiconductor, which in turn inhibits charge separation and lowers the voltage of the solar cell (Peck and van der Linde, 2010). Solar PV panels are 0.4-0.5% less efficient per 1℃ (1.8℉) increase in ambient temperature, above 25℃ (77℉) (Chemisana & Lamnatou, 2014).
- Jahanfar et al. (2020) created an evapotranspiration model for solar PV-integrated green roofs, finding that shading and wind-shielding from solar PV panels directly block solar radiation onto the underlying plants, reducing evapotranspiration rates and by extension, water use. Additionally, the panels shield the plants from wind, further reducing evapotranspiration. At the same time, reduced solar PV temperatures increase efficiency and life span of the panels.

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3. Questions and Answers

Question 1: What does Sustainable Urban Development entail and why are green roofs a Nature Based Solution (NBS)?

Answer 1: Sustainable urban development is a city's use of resources and space in a way that meets the needs of its residents today without negatively impacting the needs of residents in the future. This method of urban development aims to minimise damage to the environment while preserving as much of our resources as possible and transitioning to renewable resources wherever possible. The green roof is considered a Nature-Based Solution since it is a means of improving the energy efficiency of buildings, contributes to the improvement of air quality and temperature regulation of the urban area, promotes biodiversity and, in addition, participates in sustainable urban development.

Question 2: How do intensive green roofs differ from extensive green roofs, and what benefits do they bring to the environment?

Answer 2: Intensive green roofs consist of lush vegetation and may include shrubs and trees, in contrast to extensive green roofs which are characterised by a shallow, self-sustaining growing medium. Intensive green roofs therefore require high levels of maintenance compared to extensive green roofs. Both green roofs bring great benefits to the environment such as reduction of the heat island effect, improvement of air quality, improvement of comfort and social well-being, rainwater management etc.

Question 3: Please name three environmental, social and economic parameters that improve green roofs.

Answer 3: The parameters for improvement through environment are improvement of air quality, improvement of water management and reduction of the heat island effect. The economic parameters are improvement of employability and land use, as well as reduction of the building's energy consumption and thus the electricity bill. Finally, the social parameters would be reduction of environmental noise, improvement of building aesthetics and improvement of the sense of well-being.

Question 4: Please briefly explain the different phenomena that occur on green roofs for energy savings.

Answer 4: The main phenomena for energy savings in green roofs are:

1- The properties of vegetation which are defined with plant characteristics such as solar energy consumption through photosynthesis and evapotranspiration.

2- Improvement of thermal insulation through the reduction of the thermal transmittance of the roof.

3- Increase of the thermal mass of the different layers that form the green roof, especially that of the substrate and vegetation.

Question 5: Define the thermal conductivity parameter K and explain how it affects the thermal transmittance U.

Answer 5: Thermal conductivity K is the ability to transmit heat measured by the quantity known as the coefficient of thermal conductivity. The lower the value of K, the better the insulation of the material. The following equation shows its relationship with the thermal transmittance U.

$$U = \frac{K}{t} + h_i$$

Therefore, the higher the conductivity, the higher the transmittance and the lower the insulation of the roof.

Question 6: Why can a green roof be considered a passive element of energy efficiency in a building?

Answer 6: From an energy point of view, green roofs can be considered passive elements in buildings, since they are installed in the design of the building to reduce its energy consumption. Green roofs installed on the roof of a building modify the energy transfer between the building envelope and the exterior, increasing the albedo of the roof, increasing the thermal inertia of the roof and attenuating the temperature values supported by the roof.

Question 7: Please, explain why green roofs reduce stormwater runoff.

Answer 7: Mainly for two reasons: first, they increase the amount of water that remains on the roof after a storm and second, they reduce the rate at which water flows from the roof to the storm drain.

Question 8: Why is it considered that green roofs can reduce rainwater pollution?

Answer 8: Mainly because the plants that make up the green roof can absorb and filter pollutants from the rain, thus dampening the effects of acid rain and protecting the building.

Question 9: Please, if possible, explain a rainwater harvesting system on green roofs.

Answer 9: the rainwater harvesting system can be installed in all types of buildings (houses, factories or companies) to achieve a sustainable benefit. The system consists of a tank or cistern in which water not absorbed by plants is stored. This water is recirculated to the roof through a pump, providing an economic benefit (lower water consumption) and an environmental benefit (recycling) for the irrigation of the green roof.

Question 10: Define what a nature-based solution is according to the International Union for Conservation of Nature.

Answer 10: The International Union for Conservation of Nature (IUCN) defines nature-based solutions (also referred to as NBS) as "actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits.

Question 11: Lists 10 benefits of green roofs.

Answer 11: Help to manage stormwater, improve biodiversity, mitigate the urban heat island effect, reduce energy consumption, produce benefits to mental health, purify the air, enables new areas for urban agriculture, boost the economy and act like an acoustic and fire barrier.

Question 12: Explain the economic benefits produced by the green roofs.

Answer 12: Green roofs can provide green job generation through the production, installation and maintenance of green roofs and also can provide investment benefits for building developers and owners and provide marketing opportunities to the building. In addition, green roofs increase the life span of buildings.

Question 13: Please discuss which renewable technologies can be integrated into green roofs.

Answer 13: Among the different technologies, the use of photovoltaic panels for the generation of electricity with solar energy stands out. Wind turbines can also be used to make use of wind energy or plants for biomass generation.

Question 14: Please explain the different benefits of integrating photovoltaic panels on green roofs.

Answer 14: Among the main benefits are increased efficiency of the solar panels due to the reduction of the ambient temperature. Generation of electric energy and consequent reduction of the cost of the electric bill. Protection of the plants used in the green roof against adverse weather conditions, better use of space and increased life span of the membrane layer. Support systems can also be used for the panels that serve for the roof structure, reducing the use of materials.

Question 15: On which two parameters does the orientation of a photovoltaic panel mainly depend? Please explain.

Answer 15: The main parameters on which it depends are:

- Tilt of the panels with respect to the horizontal plane.
- Azimuth (orientation), i.e. deviation, in degrees, with respect to the south. That is, -90º would be the East orientation, 0º the South orientation and 90º the West orientation.

4. Multiple Choice Questions

1. **Which of the following characteristics does not correspond to extensive green roofs?**
   a) Waterproofing layer
   b) High maintenance of vegetation
   c) Lightweight roofing system
   d) Minimum substrate layer (between 5 and 15 cm)

2. **Select the false option about the benefits of green roofs to urban areas.**
   a) Increase biodiversity
   b) Improve social welfare
   c) Reduce heat island effect
   d) Generate a store of drinking water

3. **Select which of the following is the correct answer regarding green roof energy saving phenomena.**
   a) As vegetation properties photosynthesis and evapotranspiration, as well as plant reflectivity, reduction of the thermal transmittance of the building and increase of the thermal mass of the layers.
   b) As plant properties photosynthesis and evapotranspiration, as well as plant color, reduction of the thermal resistivity of the building and increase of the thermal mass of the layers.
   c) It mainly focuses on the decrease of the transmittance of the green roof, although some plant phenomena related to solar energy consumption are also affected. It does not depend on the thermal mass of the layers.
   d) All answers are true.

4. **Select the correct option: Which layers have the greatest influence on thermal insulation?**
   a) Insulation layer, root barrier and substrate.
   b) Waterproof membrane, vegetation and filter layer.
   c) Insulation layer, drainage and substrate.
   d) Insulation layer, waterproof membrane and filter layer.

5. **To which parameter does the following definition correspond? "*Physical property of materials that measures the amount of energy an element passes through in a unit of time.*"**
   a) Thermal conductivity
   b) Thermal diffusivity
   c) Specific heat
   d) Thermal transmittance

6. **On which roofs do you get the most energy benefit from installing a green roof?**
    a) The highest energy saving potential corresponds to those cases where the green roof is installed on poorly insulated buildings.
    b) The greatest potential for energy savings corresponds to cases where the green roof is installed on highly insulated buildings.
    c) Green roofs depend only on the type of vegetation.
    d) Energy savings are not measurable.

7. **Select the false option about green roof water management:**
    a) Green roofs help regulate stormwater and mitigate the effects of pollutant rainfall such as acid rain.
    b) Green roofs can filter water to be considered drinking water.
    c) Choosing plants with higher evapotranspiration rates increases the rainwater absorption of a vegetative cover.
    d) Green roofs can be a key element of a stormwater management plan.

8. **On what factors does the ability of green roofs to absorb and retain rainwater depend?**
    a) The drainage layer, the growing medium, the plants (or vegetation), the slope of the roof, the season and climate and the roof size.
    b) It mainly depends on the waterproof membrane, as it is the one that retains the water.
    c) The drainage layer, the growing medium, the plants (or vegetation), the slope of the roof, the season and climate, the size of the roof and the type of building according to its use (residential or commercial).
    d) Green roofs can retain water but not absorb it.

9. **Select the false answer about multi-layer drainage systems:**
    a) Use different layers to increase impermeability or vegetation cover.
    b) Can also serve as a reservoir and are designed to store water in addition to draining.
    c) They can be covered with a filter fabric, or a layer of synthetic geocomposite of rigid plastic filaments.
    d) They are heavier and store less water than granular layers.

10. **Select the false answer:**
    a) Green roofs help the spread of fires because plants are fuels.
    b) Green roofs protect buildings from fires because plants have high levels of moisture.
    c) Green roofs acts as an acoustic barrier improving the quality of live.
    d) Green roof can be used as farming land.

11. **Select the correct answer:**
    a) Green roofs produce benefits to local economy.
    b) a and c are both correct.
    c) Green roofs protect animals and vegetables species.
    d) Green roof can be harmful to the ecological balance of the cities.

12. **With respect to the Urban Heat Island (UHI) effect, select the false option:**
   a) Increase energy consumption and can cause heat-related illness.
   b) As it is a complex effect, it can be modelled with simulation tools such as ENVI-met or TRNSYS.
   c) This effect is common in cities where natural landscapes, which absorb a significant portion of solar radiation to create steam, have been replaced with non-reflective surfaces.
   d) It is a simple effect that occurs in urban areas, it appears and disappears by itself without any measure.

13. **Which of the following is not a benefit of integrating renewable technologies into green roofs?**
   a) Protection of the plants used in the green roof against adverse weather conditions.
   b) Increased efficiency of the solar panels due to the reduction of the ambient temperature.
   c) Makes the green roof maintenance-free.
   d) On-site generation of renewable energy.

14. **PVGIS software used for the calculation of photovoltaic systems:**
   a) It allows to obtain the optimal position of solar panels in different parts of Europe (and other installations outside Europe). For this purpose, the inclination and azimuth are defined, and it also allows three different types of installations: grid-connected PV systems, tracking PV and off-grid PV systems.
   b) It allows to obtain the optimal position of solar panels in different parts of Europe (and other installations outside Europe) and only allows to obtain the case of off-grid installations.
   c) It contains an extensive database since 2005 on solar radiation.
   d) Answers a) and c) are true.

15. **Select the incorrect answer about research on renewable technologies in green roofs:**
   a) According to studies, it is necessary to introduce as many solar panels as possible on green roofs to improve the roof's performance and use the surplus energy to generate drinking water.
   b) Solar PV panels are 0.4-0.5% less efficient for every 1 ℃ (1.8 ℉) increase in ambient temperature above 25℃ (77℉), this is why the use of green roofs helps improve panel efficiency.
   c) In 2020, it was discovered that the shading and wind protection of solar PV panels directly blocks solar radiation on the underlying plants, reducing evapotranspiration rates and, consequently, water consumption.
   d) A comparison of two solar-clad roofs in Sydney, Australia, one bare under its panels and the other adorned with native grasses and plants, revealed that the green roof panels were, on average, 3.63% more efficient, producing a daily average 13% more than the conventional roof.

5. Case studies

Two case studies on module 2: "*Sustainable roofing methods*" are presented below. On the one hand, it will show how to calculate the energy benefits of green roofs, and, on the other hand, it will propose a criterion for the selection of green roof vegetation according to different variables studied in the module. The following data are available for both cases study:

1. Data of the dwelling and of the city in which the green roof is installed.

City	Average temperature in summer (ºC)	Comfort temperature (ºC)	Weather Details	h_{ext} (W/K·m^2)
Valencia (Spain)	26	24	Warm and dry	10

Table 2. Information on the cities where the green roof is to be installed.

Roof area (m^2)	Typical energy consumption of a 100 m^2 house in Valencia (KWh/year)	Percentage of annual energy consumption due to heat flow through the roof (%)
100	4,500	30

Table 3. Details of the building in which the green roof is to be installed.

2. Data on the roof materials and the materials of which the green roof will be composed.

Layer	Thermal conductivity (W/m·K)	Thickness (m)
Insulating layer (XPS)	0.033	0.04
Brick Roof	0.7	0.1

Table 4. Properties of roof and green roof materials.

Green roof Layer	Bulk density (kg/m^3)	Thermal diffusivity (m^2/s)	Specific heat (J/Kg·K)	Thickness (cm)
Soil-Substrate	1,800	$2.73 \cdot 10^{-6}$	1,169.603	15

Table 5. Properties and data of the soils substrate later of the green roof materials.

3. Characteristics and details of plants used for green roofs.

Plants	Thermal conductivity (W/m·K)	Resistance to the lack of water (scale 0-10)	Medium length (cm)	Cold resistance (scale 0-10) (*)	Heat resistance (scale 0-10) (**)	Minimum temperature (ºC)	Maximum temperature (ºC)
A- Viola Heredacea	1.67	3	15	9.09	9.21	-10	35
B- Aptenia Cordifolia	0.5	4	15	2.72	10	-3	38
C- Brachyscome multífida	0.56	8	60	0	10	5	38
D- Gazania	0.56	6	25	4.54	7.89	-5	30

Table 6. Physical characteristics and details of plants suitable for green roofs.

(*) Cold resistance (scale 0-10) [0=0ºC to 10=-11ºC]
(**) Heat resistance (scale 0-10) [0=25ºC to 10=38ºC]

5.1. Case study 1. Calculation of the energy savings generated by a green roof in the city of Valencia (Spain).

In the first case study we are going to calculate the energy savings from the installation of a green roof depending on the vegetation installed on the roof. For the realization of this exercise some simplifications and approximate data will be made with the intention of facilitating its understanding and its realization. The steps for its resolution are:

I. Problem statement and data reading.

In order to calculate the energy savings obtained by installing a green roof, we must think about how a green roof improves the efficiency of the building and reduces the energy consumption produced mainly by thermal conditioning.

As explained above, the main advantage of a green roof is the improvement of the roof insulation. To understand the insulation of the roof without a green roof, we need to look at the properties of the different layers that make up the roof and their thickness. Specifically, for this exercise, the typical values for a brick roof with an XPS insulation layer have been used.

In addition, for the case of the green roof, we must also know the properties of the substrate, of which its thermal conductivity must be obtained from its apparent density, its thermal diffusivity and its specific heat, as well as the conductivity of the chosen plant and the average length they reach.

To calculate the heat flow through the roof, the comfort temperature inside the building and the average summer temperature of the installation site are selected, as well as a typical value of the convection coefficient of the outside air.

In this case the location of the green roof has been chosen in Valencia (Spain). The tables above provide the total area of the bare roof and the typical annual consumption of a 100 m^2 building.

II. Calculation of the annual energy transmitted through the roof without green roof.

To start with, an approximation of the heat flux transmitted by the roof is calculated; in this case, heat would tend to enter the building, overheating it. Introducing the equation (2) - *Heat transfer coefficient U* into the equation (1) - *Heat transferred Q*, he following equation is obtained, which will give the heat per square meter ($\frac{W}{m^2}$).

By using equations (1)& (2)

$$Q\left(\frac{W}{m^2}\right)=\frac{T_{amb}-T_{comfort}}{\frac{1}{h_{ext}}+\frac{th_{insulation}}{K_{insulation}}+\frac{th_{roof}}{K_{roof}}}$$

Entering the values from tables 2 and 4 we obtain the following result:

$$Q_0=\frac{26-24}{\frac{1}{10}+\frac{0.04}{0.033}+\frac{0.1}{0.7}}=\mathbf{1.37}\ \frac{\boldsymbol{W}}{\boldsymbol{m^2}}$$

Next, let proceed to calculate the total annual energy transmitted through the roof, which in other words, is the total energy we have to supply per year to offset the losses in the roof in order to maintain our building at the comfort temperature. For this purpose, energy is calculated as the power consumed per unit of time. In this case, we obtained that the heat transmitted per unit area is 1.37 $(\frac{W}{m^2})$. Therefore, to calculate the annual energy, it is multiplied by the seconds of a year and the corresponding conversion is applied to $\boldsymbol{KWh}$.

$$E_0=Q_0\cdot A\cdot t=1.37\cdot 100\cdot 31{,}536{,}000\cdot\frac{1}{1{,}000\cdot 3{,}600}=\mathbf{1{,}200.12}\ \frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

In addition, the data are consistent since the result of the thermal gain through the roof is approximately the energy consumption of the building per over 30% of losses through the roof (Data from table 3.) Therefore, the result is as follows: $4{,}500\ KWh/year*0.3=1350\ KWh/year$ that are transmitted through the roof and that (in estimated terms) have a similar order of magnitude to those calculated in detail by the formula.

III. Calculation of the annual energy transmitted through the roof with green roof depending on the vegetation.

The purpose of this section is to calculate the heat transmitted through the green roof with the plants located on the green roof (considering that all plants of the same type are used).

In this case the same calculations are made as in the previous section but adding the thickness and conductivity of the substrate and the plants.

On the one hand, the conductivity of the soil-substrate is calculated using equation 3 of the notes and the data provided in table 5:

$$K_{soil} = \alpha \cdot \rho \cdot Cp = 2.73 \cdot 10^{-6} \cdot 1{,}800 \cdot 1{,}169.603 = \mathbf{5.74}\ \frac{\boldsymbol{W}}{\boldsymbol{m \cdot K}}$$

On the other hand, once the soil conductivity K has been calculated, the energy transmitted through the green roof can be calculated. For this purpose, considering the different layers of which the green roof is composed, it must be taken into account that the conductivity of the insulation, of the brick roof, of the soil and of the plants will be considered within the equation.

The procedure is the same as in section II, but it will be carried out for each type of plant (table 6) in order to deduce which plant offers the best thermal insulation.

a) Viola Heredacea

First, the heat transmitted from the building to the outside, through the different layers of the green roof, is calculated.

$$\mathrm{Q} = \frac{T_{amb} - T_{comfort}}{\frac{1}{h_{ext}} + \frac{th_{insulation}}{K_{insulation}} + \frac{th_{roof}}{K_{roof}} + \frac{th_{soil}}{K_{soil}} + \frac{th_{plants}}{K_{plants}}}$$

To obtain the heat, the data in tables 2, 4, 5 and 6 are entered, resulting in the following value**:**

$$Q_A = \frac{26 - 24}{\frac{1}{10} + \frac{0.04}{0.033} + \frac{0.1}{0.7} + \frac{0.15}{5.74} + \frac{0.15}{1.67}} = \mathbf{1.27}\frac{\boldsymbol{W}}{\boldsymbol{m^2}}$$

Finally, the energy transmitted annually is calculated in the same method as in the previous section.

$$E_A = Q_A \cdot A \cdot t = 1.27 \cdot 100 \cdot 31{,}536{,}000 \cdot \frac{1}{1{,}000 \cdot 3{,}600} = \mathbf{1{,}115.26}\ \frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

b) Aptenia cordifolia

Follow the same procedure as in (a) for the data of the plant of variety "*Aptenia cordifolia*".

$$Q_B = \frac{26 - 24}{\frac{1}{10} + \frac{0.04}{0.033} + \frac{0.1}{0.7} + \frac{0.15}{5.74} + \frac{0.15}{0.5}} = \mathbf{1.12}\frac{\boldsymbol{W}}{\boldsymbol{m^2}}$$

$$E_B = Q_B \cdot A \cdot t = 1.12 \cdot 100 \cdot 31{,}536{,}000 \cdot \frac{1}{1{,}000 \cdot 3{,}600} = \mathbf{983.65}\ \frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

c) Brachyscome multífida

Follow the same procedure as in (a) for the data of the plant of variety "*Brachyscome multífida*".

$$Q_C = \frac{26-24}{\frac{1}{10}+\frac{0.04}{0.033}+\frac{0.1}{0.7}+\frac{0.15}{5.74}+\frac{0.6}{0.56}} = \mathbf{0.78}\,\frac{\boldsymbol{W}}{\boldsymbol{m^2}}$$

$$E_C = Q_C \cdot A \cdot t = 0.78 \cdot 100 \cdot 31{,}536{,}000 \cdot \frac{1}{1{,}000 \cdot 3{,}600} = \mathbf{686.37}\,\frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

d) Gazania

Follow the same procedure as in (a) for the data of the plant of variety "*Gazania*".

$$Q_D = \frac{26-24}{\frac{1}{10}+\frac{0.04}{0.033}+\frac{0.1}{0.7}+\frac{0.15}{5.74}+\frac{0.25}{0.56}} = \mathbf{1.03}\,\frac{\boldsymbol{W}}{\boldsymbol{m^2}}$$

$$E_D = Q_D \cdot A \cdot t = 1.03 \cdot 100 \cdot 31{,}536{,}000 \cdot \frac{1}{1{,}000 \cdot 3{,}600} = \mathbf{908.93}\,\frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

IV. Calculation of annual savings according to the vegetation used.

In this section, the savings produced by introducing the green roof are finely calculated with respect to the initial case in which there was no green roof and only the brick roof. The energy savings for this particular case will also depend on the type of plant used. Finally, the plant that obtains the optimum savings for this case study will be obtained.

a) Viola Heredacea

The first stage is to calculate the savings obtained by the green roof and the type of plant chosen. This saving is calculated as the difference between the energy transmitted Q_0 without the green roof minus the energy transmitted Q_A by the green roof.

$$\Delta E_A = E_0 - E_A = 1{,}200.12 - 1{,}115.26 = \mathbf{84.86}\,\frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

Therefore, with the green roof, energy savings of 84.86 KWh/year are obtained. Therefore, if we consider this energy saving with respect to the total energy consumption of the house, we will obtain the percentage of savings in terms of energy that the introduction of the green roof in the building represents.

$$\Delta E_A(\%) = \left(1 - \frac{4{,}500 - 84.86}{4{,}500}\right) \cdot 100 = \mathbf{1.885}\ \%$$

b) **Aptenia cordifolia**

The same procedure is followed for the case of the "Aptenia cordifolia".

$$\Delta E_B = Q_0 - Q_B = 1{,}200.12 - 983.65 = \mathbf{216.47} \frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

$$\Delta E_B(\%) = \left(1 - \frac{4{,}500 - 216.47}{4{,}500}\right) \cdot 100 = \mathbf{4.81}\ \%$$

c) **Brachyscome multífida**

The same procedure is followed for the case of the "Brachyscome multífida".

$$\Delta E_C = Q_0 - Q_C = 1{,}200.12 - 686.37 = \mathbf{512.75} \frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

$$\Delta E_C(\%) = \left(1 - \frac{4{,}500 - 512.75}{4{,}500}\right) \cdot 100 = \mathbf{11.39}\ \%$$

d) **Gazania**

The same procedure is followed for the case of the "Gazania".

$$\Delta E_D = Q_0 - Q_D = 1{,}200.12 - 908.93 = \mathbf{291.19} \frac{\boldsymbol{KWh}}{\boldsymbol{year}}$$

$$\Delta E_D(\%) = \left(1 - \frac{4{,}500 - 291.19}{4{,}500}\right) \cdot 100 = \mathbf{6.47}\ \%$$

V. Conclusions

Type of plant	A- Viola Heredacea	B- Aptenia Cordifolia	C- Brachyscome multífida	D- Gazania
Energy savings (%)	1.885 %	4.81 %	11.39 %	6.47 %

Table 7. Table of results for case study 1.

Several conclusions can be drawn from the results obtained in Table 2:

1- Energy savings are highly dependent on the choice of vegetation.

2- The estimations yield consistent results, since in these examples there are three values with savings between 1 and 7%, which are typical values for savings in buildings with thermal insulation on roofs, and one value with a slightly higher saving of 11%, which is explained by the properties and height of the selected plant.

3- In addition, it is noted that the plant that provides the greatest savings in terms of energy for the building is the “Brachyscome multífida”.

6.1. Case study 2. Selection of the most suitable plant typology in a green roof according to different sustainability criteria.

The second case study consists of the development and application of a criterion for the selection of the type of vegetation to be used. For this purpose, the data from the previous tables and the energy savings obtained for each plant will be used. The steps to be followed are detailed below:

I. Problem statement and data reading.

The objective of this exercise is to choose the most suitable plant, based on the different qualities of the plants and the characteristics of the climate of the chosen location, in this case, Valencia (Spain).

For the approach of this exercise, we have assessed that the selection of the vegetation of the roof should not only depend on its impact on energy savings since the selected plant must be able to survive the climate of the building site, depending as little as possible on maintenance such as pruning or irrigation in order to reduce the costs of care of the roof.

The parameters to be considered in this case are:

Heat Resistance (HR)	The **maximum temperature** the plants can withstand and the historical maximum temperature of the site
Cold Resistance (CR)	The **minimum temperature** that the plants can support and the historical minimum temperature of the site
Resistance to the lack of water (LW)	The amount of **water consumed** by the plants and the frequency of rainfall at the site
Energy saving capacity (EC)	The **capacity to save energy**

These four parameters will be evaluated for each plant with a score from 0 to 10 depending on the characteristics of the plants and their relationship with the environment. In addition, each parameter has been assigned a weighting according to the importance considered for each location. The weighted sum of the results will be the final score that will allow comparison of the plants and the highest value will be the plant that best suits the given conditions.

II. Assessment of the importance of each variable depending on the climatic conditions of the site.

In the case of Valencia, it is a hot city with prolonged droughts. It is not a cold climate and temperatures very rarely fall below 0 ºC. The values can be seen in Table 2 at the beginning of the case study section.

Therefore, the following weighting has been made for each of the chosen criteria:

- **K_1 - Ability to survive high temperatures**: 30%.
- **K_2 - Tolerance to water shortages**: 30%.
- **K_3 - Energy saving capacity**: 35%.
- **K_4 - Ability to survive low temperatures**: 5%.

This has been the weighting chosen for the city of Valencia (Spain) but depending on the location and who selects the vegetation it could change.

The following table shows the data obtained for each type of plant on energy savings in % and scaled according to the standard values of energy savings.

Plants	Annual energy savings (%)	Annual energy saving (scale 0-10) (*)
A- Viola Heredacea	1.885	1.57
B- Aptenia Cordifolia	4.81	4.00
C- Brachyscome multífida	11.39	9.49
D- Gazania	6.47	5.39

Table 8. Green roof savings results per plant

(*) The scale has been made from 1 to 10 taking into account minimum savings values of 0 as 0 and maximum values of up to 12% as 10.

III. Calculation of the weighted score for the Plant Suitability.

For the calculation of the final qualification, the weighted sum has been calculated according to the following equation:

$$Plant_{suitability} = HR \cdot K_1 + LW \cdot K_2 + EC \cdot K_3 + CR \cdot K_4$$

The above formula will be used to calculate the suitability of each plant, according to the K parameters and the data in Table 8.

- $\textbf{Viola Heredacea}_{suitability} = 0.3 \cdot 9.21 + 0.3 \cdot 8 + 0.35 \cdot 1.57 + 0.05 \cdot 9.09 = \mathbf{6.16}$
- $\textbf{Aptenia cordifolia}_{suitability} = 0.3 \cdot 10 + 0.3 \cdot 7 + 0.35 \cdot 4 + 0.05 \cdot 2.72 = \mathbf{6.63}$
- $\textbf{Brachyscome multífida}_{suitability} = 0.3 \cdot 10 + 0.3 \cdot 4 + 0.35 \cdot 9.49 + 0.05 \cdot 0 = \mathbf{7.52}$
- $\textbf{Gazania}_{suitability} = 0.3 \cdot 7.89 + 0.3 \cdot 5 + 0.35 \cdot 5.39 + 0.05 \cdot 4.54 = \mathbf{5.98}$

IV. Conclusions

With these calculations, we know then that the best plant for taking into account the climatic conditions of Valencia and the insulating capacity of the vegetation is the Brachyscome multífida plant, with a score of 7.52, highlighting its resistance to heat and energy savings that it provides and the worst option would be the Gazania, with a 5.98, which is a lower energy savings and lower resistance to heat but with better resistance to lack of rain to the cold.

7. Practical exercises

In the following section, two practical exercises are proposed based on the case studies seen in this module 2.

7.1. Practical exercise 1: Calculation of the annual energy savings depending on vegetation in Warsaw (Poland).

Calculate the percentage of energy savings produced by the use of a green roof on a building located in Warsaw (Poland). Calculate this value (%) for each plant typology given in Table X.

The data provided about the building, the location and the green facility that will be necessary for the resolution of the exercise are listed below:

1. Data of the dwelling and of the city in which the green roof is installed.

City	Average temperature in summer (°C)	Comfort temperature (°C)	Weather Details	h_{ext} (W/K·m^2)
Warsaw (Poland)	19	24	Cold and dry	15

Table 9. Practical Exercise 1: Information on the city where the green roof is to be installed.

Roof area (m^2)	Typical energy consumption of a 100 m^2 house in Warsaw (KWh/year)	Percentage of annual energy consumption due to heat flow through the roof (%)
100	9,000	30

Table 10. Practical Exercise 1: Details of the building in which the green roof is to be installed.

2. Data on the roof materials and the materials of which the green roof will be composed

Layer	Thermal conductivity (W/m·K)	Thickness (m)
Insulating layer (XPS)	0.033	0.04
Brick Roof	0.7	0.1

Table 11. Practical Exercise 1: Properties of roof and green roof materials.

Green roof Layer	Bulk density (kg/m^3)	Thermal diffusivity (m^2/s)	Specific heat (J/Kg·K)	Thickness (cm)
Soil-Substrate	1,800	$2.73 \cdot 10^{-6}$	1,169.603	15

Table 12. Practical Exercise 1: Properties and data of the soils substrate later of the green roof materials.

3. Characteristics and details of plants used for green roofs.

Plants	Thermal conductivity (W/m·K)	Resistance to the lack of water (scale 0-10)	Medium length (cm)	Cold resistance (scale 0-10) (*)	Heat resistance (scale 0-10) (**)	Minimum temperature (ºC)	Maximum temperature (ºC)
A- Viola Heredacea	1.67	3	15	9.09	9.21	-10	35
B- Aptenia Cordifolia	0.5	4	15	2.72	10	-3	38
C- Brachyscome multífida	0.56	8	60	0	10	5	38
D- Gazania	0.56	6	25	4.54	7.89	-5	30

Table 13. Practical Exercise 1: Physical characteristics and details of plants suitable for green roofs.

(*) Cold resistance (scale 0-10) [0=0ºC to 10=-11ºC]
(**) Heat resistance (scale 0-10) [0=25ºC to 10=38ºC]

Solution

First, the **annual energy transmitted** through the roof without vegetation cover is calculated through the following formula:

By using equations (1)& (2)

$$Q\left(\frac{W}{m^2}\right) = \frac{T_{amb} - T_{comfort}}{\frac{1}{h_{ext}} + \frac{th_{insulation}}{K_{insulation}} + \frac{th_{roof}}{K_{roof}}} = \frac{19 - 24}{\frac{1}{15} + \frac{0.04}{0.033} + \frac{0.1}{0.7}} = \mathbf{-3.51\ \frac{W}{m^2}}$$

In this case, the transmitted heat is negative because the outside temperature is lower than the comfort temperature due to the cold climate. Therefore, the roof is giving up heat to the environment.

The transmitted energy is calculated in absolute value and the result is as follows:

$$E = |Q| \cdot A \cdot t = 3.51 \cdot 100 \cdot 31{,}536{,}000 * \frac{1}{1{,}000 \cdot 3{,}600} = 3{,}074.76\ \frac{KWh}{year}$$

On the other hand, it is found that the heat given up through the roof is close to the estimated 30%: 9,000 KWh/year *30%=2,700 KWh/year.

The annual energy transmitted through the green roof is then calculated as a function of vegetation.

To do this, first the conductivity of the soil is calculated:

$$K_{soil} = \alpha * \rho * Cp = 2.73 \cdot 10^{-6} \cdot 1{,}800 \cdot 1{,}169.603 = 5.74\ \frac{W}{m \cdot K}$$

After that, using the following formula, the heat transmitted by the green roof is calculated for each of the given plants:

$$\mathrm{Q} = \frac{T_{amb} - T_{comfort}}{\frac{1}{h_{ext}} + \frac{th_{insulation}}{K_{insulation}} + \frac{th_{roof}}{K_{roof}} + \frac{th_{soil}}{K_{soil}} + \frac{th_{plants}}{K_{plants}}}$$

Finally, the annual energy savings are calculated according to the vegetation used.

$$E = |Q| \cdot A \cdot t$$

$$\Delta E = E_0 - E$$

$$\Delta E(\%) = \left(1 - \frac{E_0 - E}{E_0}\right) \cdot 100$$

a) Viola Heredacea

$$Q_A = \frac{19 - 24}{\frac{1}{15} + \frac{0.04}{0.033} + \frac{0.1}{0.7} + \frac{0.15}{5.74} + \frac{0.15}{1.67}} = -3.25\frac{W}{m^2}$$

$$E_A = |Q| \cdot A \cdot t = 3.25 \cdot 100 \cdot 31{,}536{,}000 \cdot \frac{1}{1{,}000 \cdot 3{,}600} = 2{,}848.59\ \frac{KWh}{year}$$

$$\Delta E_A = E_0 - E_A = 3{,}074.76 - 2{,}848.59\ = 226.17\frac{KWh}{year}$$

$$\Delta E_A(\%) = \left(1 - \frac{9{,}000 - 2{,}26.17}{9{,}000}\right) * 100 = 2.513\ \%$$

b) Aptenia cordifolia

$$Q_B = \frac{19-24}{\frac{1}{15}+\frac{0.04}{0.033}+\frac{0.1}{0.7}+\frac{0.15}{5.74}+\frac{0.15}{0.5}} = -2.86\,\frac{W}{m^2}$$

$$E_B = |Q_B| * A * t = 2.86 \cdot 100 \cdot 31{,}536{,}000 \cdot \frac{1}{1{,}000 \cdot 3{,}600} = 2{,}503.03\ \frac{KWh}{year}$$

$$\Delta E_B = E_0 - E_B = 3{,}074.76 - 2{,}503.03 = 571.73\,\frac{KWh}{year}$$

$$\Delta E_B(\%) = \left(1 - \frac{9{,}000 - 571.73}{9{,}000}\right) * 100 = 6.35\ \%$$

c) Brachyscome multífida

$$Q_C = \frac{19-24}{\frac{1}{15}+\frac{0.04}{0.033}+\frac{0.1}{0.7}+\frac{0.15}{5.74}+\frac{0.6}{0.56}} = -1.98\,\frac{W}{m^2}$$

$$E_C = |Q_C| * A * t = 1.98 \cdot 100 \cdot 31{,}536{,}000 \cdot \frac{1}{1{,}000 \cdot 3{,}600} = 1{,}738.64\ \frac{KWh}{year}$$

$$\Delta E_C = E_0 - E_C = 3{,}074.76 - 1{,}738.64 = 1{,}336.12\,\frac{KWh}{year}$$

$$\Delta E_C(\%) = \left(1 - \frac{9{,}000 - 1{,}336.12}{9{,}000}\right) \cdot 100 = 14.84\%$$

d) Gazania

$$Q_D = \frac{19-24}{\frac{1}{15}+\frac{0.04}{0.033}+\frac{0.1}{0.7}+\frac{0.15}{5.74}+\frac{0.25}{0.56}} = -2.64\,\frac{W}{m^2}$$

$$E_D = |Q_D| \cdot A \cdot t = 2.64 \cdot 100 \cdot 31{,}536{,}000 \cdot \frac{1}{1{,}000 \cdot 3{,}600} = 2{,}312.31\,\frac{KWh}{year}$$

$$\Delta E_D = E_0 - E_D = 3{,}074.76 - 2{,}312.31 = 762.45\,\frac{KWh}{year}$$

$$\Delta E_D(\%) = \left(1 - \frac{9{,}000 - 762.45}{9{,}000}\right) \cdot 100 = 8.47\ \%$$

Type of plant	A- Viola Heredacea	B- Aptenia Cordifolia	C- Brachyscome multífida	D- Gazania
Energy savings (%)	2.513	6.35	14.84	8.47

Table 14. Practical exercise 1: results per type of plant.

A maximum saving of 14.84% is achieved with vegetation Brachyscome multífida.

7.2. Practical exercise 2: Final selection of vegetation.

According to the procedure proposed in case study 2, determine which type of plant is best suited to the given conditions for the green roof located in Warsaw (Poland).

The characterization parameters K take the following values for Warsaw:

- **K_1 - Ability to survive high temperatures**: 5%.
- **K_2 - Tolerance to water shortages**: 25%.
- **K_3 - Energy saving capacity**: 35%.
- **K_4 - Ability to survive low temperatures**: 35%.

The characteristics and details of the plants used for green roofs located in table 13 of practical exercise 1should be used.

In this case, the energy savings data for each plant are provided, but they correspond to the results obtained in practical exercise 1. In addition, the scaled rating from 1 to 10 is also provided.

Plants	Annual energy savings (%)	Annual energy saving (scale 0-10) (*)
A- Viola Heredacea	2.513	1.67
B- Aptenia Cordifolia	6.35	4.23
C- Brachyscome multífida	14.84	9.89
D- Gazania	8.47	5.64

Table 15. Practical exercise 2: Green roof savings results per plant.

(*) The scale has been made from 1 to 10 taking into account minimum savings values of 0 as 0 and maximum values of up to 15% as 10.

Resolution:

According to case study 2, the suitability of the plant for the green roof will be obtained through the following formula:

$$Plant_{suitability} = HR \cdot K_1 + LW \cdot K_2 + EC \cdot K_3 + CR \cdot K_4$$

With the data obtained in table 13 (practical exercise 1) and table 15, they are introduced in the equation giving the following results:

- $\textbf{Viola Heredacea}_{suitability} = 0.05 \cdot 9.21 + 0.25 \cdot 8 + 0.35 \cdot 1.67 + 0.35 \cdot 9.09 = \mathbf{6.22}$
- $\textbf{Aptenia cordifolia}_{suitability} = 0.05 \cdot 10 + 0.25 \cdot 7 + 0.35 \cdot 4.23 + 0.35 \cdot 2.72 = \mathbf{4.68}$
- $\textbf{Brachyscome multífida}_{suitability} = 0.05 \cdot 10 + 0.25 \cdot 4 + 0.35 \cdot 9.89 + 0.35 \cdot 0 = \mathbf{4.96}$
- $\textbf{Gazania}_{suitability} = 0.05 \cdot 7.89 + 0.25 \cdot 5 + 0.35 \cdot 5.64 + 0.35 \cdot 4.54 = \mathbf{5.2}$

For this location, according to the criteria used, the best choice would be to use the Viola Heredacea plant because of its high resistance to cold, which is essential in Varsovia, a city with a continental climate that often reaches temperatures below 0ºC.