MULTI-FACTOR ANALYSIS OF DIFFERENT GREEN ROOF PACKAGES USING INDEXES BASED ON SURFACE TEMPERATURES IN MEDITERRANEAN CLIMATE

Stefano Cascone[a],*, Antonio Gagliano[b], Tiziana Poli[c], Gaetano Sciuto[a]

[a] Department of Civil Engineering and Architecture, University of Catania, Via Santa Sofia 64, 95123, Catania, Italy

[b] Department of Electrical, Electronics and Computer Engineering, University of Catania, Viale Andrea Doria 6, 95125, Catania, Italy

[c] Politecnico di Milano, Department of Architecture, Built environment and Construction engineering, Via Ponzio 31, 20133, Milan, Italy

* Corresponding author. E-mail address: stefano.cascone@unict.it (S. Cascone)

Highlights

- Use of realistic values to characterize green roof vegetation and substrate
- Surface temperature indexes were used to evaluate the energy performance
- Six plant species and five types of substrate were examined
- Succulent plants provided the best performance in Mediterranean climate

Abstract

Green roofing is a sustainable solution for building energy saving, urban heat island mitigation, rainwater management and pollutant absorption. The objective of this research is to define the effectiveness of green roofs in Mediterranean climate. To this end, six vegetation species, different in height, leaf area index (LAI), leaf reflectivity, leaf emissivity and stomatal resistance, and five types of substrate, characterized by various thermal conductivity, density and specific heat, were considered according to the technologies currently adopted for green roofs. A matrix of possible combinations (30 plant-substrate configurations) was defined and a multi-criteria analysis was carried out, using indexes based on the surface temperatures of green roofs, to identify which green roof combination offers the highest performance. Therefore, a comprehensive ranking was defined based on the score that each green roof achieved in the performance indexes. The results show that high values of vegetation height (i.e. Salvia) LAI (>4 m^2/m^2), leaf reflectivity (>0.2) and stomatal resistance (>0.2 $mmol/m^2s$) improve green roof energy performance in the summer period. However, if the analysis is carried out for the winter period, succulent plants (i.e. Sedum) offer better performance. Finally, Heuchera yellow provides more balanced performance during both heating and cooling period. The substrate and vegetation selection are strictly correlated, thus the same plant species combined with different substrate types attained heterogeneous performance.

Keywords: Green Roof; Thermal performance; Surface temperature; Building Energy Simulation; UHI mitigation; Multi-criteria analysis

1. INTRODUCTION

In recent years, the growing phenomenon of global warming and the increasing urban development, characterized by large waterproof surfaces, have led to increased environmental and energy problems in many cities [1,2]. Consequently, researchers and designers are committed to developing sustainable solutions to reduce both the energy consumption and the pollutant emission of buildings using environment-friendly and innovative technological solutions [3,4]. One of the most widely used technological solutions in the field of bioclimatic architecture is to replace the traditional materials of flat roofs, accounting for about 25% of the horizontal surfaces in urban areas, with green roofs [5]. From the energy point of view, when the heating of external roof surfaces is greater due to the intense solar radiation, the use of green roofs reduces the surface temperature of the roof [6,7], improves the thermal insulation of the building envelope [8–10] and mitigates the incoming and outgoing heat flux through non-insulated roof [11]. In addition, green roofs result in energy savings for cooling the indoor spaces [12–14], especially when green roofs are used for the energy retrofitting of existing buildings with a low level of thermal insulation [15,16]. From the hydrological point of view, green roofs optimize stormwater management [17], contribute to the improvement of runoff water quality [18], provide natural filtration that reduces the risks of urban flooding and improves the hydrological balance of the urban areas by reducing rainwater runoff [19]. Many benefits can be highlighted from an environmental point of view. Green roofs absorb the polluting gases in the atmosphere, such as greenhouse, contributing to improve the air quality of cities [20] and recreating the natural habitats by optimizing biodiversity in urban areas [21]. These benefits deriving from the use of green roofs make it possible to mitigate the phenomenon of the urban heat island [22–25].

Many previous studies have evaluated the reduction in energy consumption for building conditioning due to the installation of green roofs by using the EnergyPlus simulation software that integrates a green roof model. Vera et. al [26] performed a parametric analysis to evaluate the influence of the main green roof design parameters on the cooling and heating loads of a stand-alone retail building in different climatic conditions. Four different Leaf Area Index (LAI) levels (0.1, 1.0, 3.0, 5.0) were studied while substrate thermal properties were selected based on the ranges for dry (0.15–0.3 W/mK) and wet substrates (0.5–1.2 W/mK). The main result obtained by this study is that the greater the LAI the greater the reduction in cooling loads due to the evapotranspiration of the vegetation-substrate system and canopy’s shading effect. Furthermore, the effect of the substrate thermal properties on the heating loads is directly related to the substrate thermal conductivity. However, substrate influence on the cooling loads depends on its thermal diffusivity. Zeng et al. [27] used a simulation to determine the optimal parameter settings for green roofs in different climate zones in China. Foliage height in green roofs ranged from 0.01 to 1.0 m, while the LAI varied between 0.001 and 5.0. With regard to energy savings, the optimum soil thickness and LAI were 0.3 m and 0.5, respectively, and the plant height was 0.3 m. The authors found that LAI is the most significant factor that influence the energy consumption. However, the parameters used in the energy simulations to characterize the vegetation and substrate layers were not obtained experimentally and do not correspond to the real vegetation and substrates used in green roofs. Peri et al. [28] highlighted the importance of a precise knowledge of vegetation and soil parameters, despite the availability of their values is still limited, to assess the green roof effects on the building thermal and energy performance.

Other studies analyzed the thermos-physical characteristics of the green roof materials. Coma et al. [29] determined experimentally the physical properties of five different substrates of extensive green roofs commonly used in Mediterranean climates. This study revealed that thermal conductivity of substrates is strongly related with their masses. Furthermore, substrates with lower organic content showed the highest rates of volumetric heat storage capacity and also provided higher time lags. The authors concluded that, when the aim is to evaluate the energy performance of green roofs, it is not accurate to assume equal properties for different type of substrates and considered them as a generic layer. Vaz Monteiro et al. [30] canopies of two succulent and four broad-leaved plant genotypes, with contrasting plant traits, were monitored alongside bare substrate, over two summers. The results suggested that succulent plants were not best suited to provide significant summertime environmental cooling and substrate insulation and that others are preferable where the delivery of these benefits is a priority.

The present research use the set of experimental data collected by these previous studies on substrates and vegetation to investigate the energy performance of green roofs in Mediterranean climate and to characterize the green roof materials in the model available in EnergyPlus.

In recent years, some studies have used indexes of performance and have defined scoring system to evaluate the thermal performance of different types of green roof according to the surface temperatures[31–33]. In addition, several previous studies have performed sensitivity analyzes of the parameters affecting the performance of green roofs [34,35]. However, in many cases these sensitivity analysis were carried out without correlating the variation of the green roof features with a specific substrate and plant species.

Differently from previous research, this study investigated the performance combination of six plant species and five types of commercial substrates, whose feature data coming from experimental surveys. So this study, differently from many literature studies, did not characterize the vegetation and substrate by varying their features, such as LAI, density and so on, between a range of continue theoretical values, but using only realistic data. Therefore, the energy performance evaluated through the simulations are referred to an effective vegetation-substrate configuration.

Furthermore, the novelty of this study is to provide for each plant-substrate configuration investigated a merit ranking with reference to different indexes of performance based on the external surface temperature, carrying out a multi-factor analysis. Three indexes, defined by Bevilacqua et al. [32] to assess the thermal performances of the different green roofs, were used to identify which green roof packages offered the highest energy performance related to the urban heat island phenomenon, energy saving and temperature fluctuations on the waterproof membrane. Thus a comprehensive merit ranking has been defined starting from the score that each green roof package achieved in any of the three performance indexes. Globally, the proposed study made it possible to identify among the 30 plant-substrate configurations which one that optimized the energy performance of the green roof in Mediterranean climate.

This study, based on a multi-factor analysis, will allow researchers and designers evaluating the energy performance of green roof in different climatic conditions and identifying which green roof packages offered the highest performance. In fact, this analysis can be used during the preliminary design stage of the green roof.

2. MATERIALS AND METHODS

2.1 The test cell

To evaluate the thermal and energy performance of different types of green roofs, a test cell used in previous literature studies was modelled in EnergyPlus [36,37].

The test cell is 1.35 m × 1.35 m × 1.35 m, with one window on the south facing wall (610 × 610 mm and U-value 1.960 W/m^{2}K). The walls and roof of the test cell are described in Table 1. The floor of the cell was made of OSB boards and XPS insulation. The U-value of the test cell envelope are reported in Table 2.

As regard the test cell, it has to be pointed out that, although the U-value of the components of the building envelope is comparable with that one of a standard buildings, due to its little volume (1.35×1.35×1.35 m) the indoor temperatures may reach values significantly different respect to a real environment. Nevertheless, the test cell allows for a comparison, in absolute values, of the results of different envelope solutions and a generalization of the results obtained.

On the other hand, when choosing a real building as case study, energy performance depends largely on the constructive characteristics of the building envelope, building occupancy, the endogenous charges, the type of equipment, etc. The results of this study have to be assumed only for the relative comparison of the performance among the different green roof packages. Therefore, the performance of each green roof packages need to be evaluated in each specific application since they are affected by the features of the building as well as the climatic zone where the green roofs are installed.

2.2 The plant species

The six plant species used as vegetation layer in the green roofs were modeled in EnergyPlus defining the height of plants, Leaf Area Index (LAI), leaf reflectivity, leaf emissivity and minimum stomatal resistance. Table 3 shows the data used, which were obtained from a previous experimental study [30].

The plants used (with key leaf characteristics in parenthesis) are the following:

- Heuchera ‘Obsidian’ (non-pubescent, purple)
- Heuchera ‘Electra’ (non-pubescent, yellow)
- Salvia officinalis ‘Berggarten’ (pubescent with grey-green hue)
- Stachys byzantina (pubescent with pale grey hue)
- Sempervivum ‘Reinhard’ (non-pubescent, succulent, light to darkgreen hue)
- Sedum mix (non- pubescent, succulent leaves, light-green hue).

All plants in the experiment were herbaceous/sub-shrub forms with potential to be integrated in green roofs, particularly if additional irrigation is provided during times of prolonged water deficit.

2.3 The substrates

The parameters required for modelling the substrate in EnergyPlus are thermal conductivity, density and specific heat, depending on the composition of the substrates. These data, shown in Table 4, were carried over from a previous literature study [29].

The composition of the substrates analyzed is also reported in Table 4. These commercial substrates are characterized by different material compositions. In particular, Substrate 1 is made up of compost, pozzolana and sand. Substrate 5 mainly consists of coco peat with a lower percentage of compost, crushed building wastes and sand. Substrate 2 and 4 are characterized by homogeneous percentages of different materials. Due to the different composition, the substrates analyzed offer different thermal performance. Finally, the composition of the Substrate 3 is characterized by a low percentage of compost.

The substrate thickness used in the simulations is 15 cm, so it could be classified as an extensive green roof.

Generally, the layers making up the green roof, from top to bottom, consist of vegetation, soil substrate, filter, drainage layer, waterproof and anti-root membrane [38]. As regard the drainage layer the filter and water storage felts, they were not included in the energy balance of the green roofs. This choice is due on the EnergyPlus limitations in considering the drainage and filter layer role and the reduced influence of these layers on the surface temperatures analyzed in this study.

2.4 The simulation settings

Thermal building simulations are performed in EnergyPlus using the “Ecoroof” module that makes it possible to define as green roof the outer layer of a building roof, specifying various features of the green roof including height of plants, LAI, leaf reflectivity, thickness/density/thermal conductivity and specific heat of soil.

The simulations were developed using the features of the test cell previously described considering that it is located in the city of Catania (Lat. 37°30.3'N, Long. 15°05.2'E), in southern Italy. During summer, the air temperature reaches high values, with peaks of over 35 °C, and air temperature fluctuations between the maximum and minimum daily reaches values of over 15 °C. All the simulations were performed for a period of one typical year, from 1st January to 31st December. Moreover, for the climatic conditions typical of the Mediterranean area, it is necessary to guarantee a minimum period of daily irrigation of the green roof, to allow the survival and proper growth of the vegetation. In this study just one-hour irrigation period between 8 and 9 p.m. was set. Therefore, the volumetric water content in each substrate and the related effects on the plant species were not investigated in this study. Values of maximum saturation moisture content of 0.50, minimum residual moisture content of 0.01 and of the initial moisture content of 0.15, remained unvaried among the different types of substrate used.

The simulations were thus conducted in free running conditions in order to allow the air temperature inside the test cell to oscillate freely. The internal (below all the roof layers) and external (on the substrate, below the vegetation) surface temperatures of the test cell were obtained as results for each selected scenario.

The heating and cooling system was subsequently inserted into the test cell when the purpose was to assess the energy demand used for conditioning. The temperature set point values were set at 20 °C for the heating period, from 1st December to 31st March, and at 26 °C for the cooling period, from 1st June to 30th September. The type of heating/cooling system used was maintained constant, in order to analyze the energy performance only in relation to the type of green roof used.

2.5 Indexes of performance

Indexes of performances as a function of the external surface temperature were used based on the relevant work of Bevilacqua et al. [32] and Teemusk and Mander [39]. These indexes may be used to characterize the behavior of the green roof in relation to the urban heat island phenomenon and energy saving. Moreover, these indexes have the advantage of being validated by high-precision experimental measurements of the surface temperatures of green roofs, allowing a direct comparison of the different green roof packages.

The first index, called Surface Temperature Reduction, STR, evaluates the reduction of surface temperatures of the green roof compared to the bare roof, in terms of average daily temperatures. It is defined by the ratio of the external surface temperature of the green roof to the external surface temperature of the bare roof. STR is evaluated in terms of average values (Eq. 1):

$$STR_{av} = \frac{T_{av}}{T_{av,bare}} \tag{1}$$

This index is representative of the sensible heat flow through the green roof and, therefore, of the consumption of energy for heating and cooling.

The second index, called External Temperature Ratio, ETR, is defined by the ratio of the maximum external surface temperature of the green roof to the average temperature of the outer air (Eq. 2):

$$ETR_{max} = \frac{T_{max}}{T_{av,air}} \tag{2}$$

This index represents the mitigation of the effect of the urban heat island due to the installation of the green roof. Consequently, reduced ETR values correspond to greater reductions in the effect of the urban heat island.

The third index, Temperature Excursion Reduction, TER, is representative of the fluctuation of the daily external surface temperature. It is defined by the ratio of the temperature fluctuation of the green roof external surface to the temperature fluctuation of the bare roof external surface (Eq. 3):

$$TER = \frac{T_{max} - T_{min}}{T_{max,bare} - T_{min,bare}} \tag{3}$$

The fluctuation of surface temperatures (thermal stress) influences the durability of roof materials, in particular of the watertight membrane. In fact, reductions in surface temperature fluctuations decrease the dilatation and contraction of materials and increase their useful life.

In order to compare the energy performance of the different plant-substrate green roof configurations, a ranking was developed summing the scores obtained for each of the above-mentioned indexes, during both the heating and the cooling period. Specifically, the score of each of 30 plant-substrate configuration is attributed based on the values achieved in each indexes. Thus, the package with the lowest performance is given a score equal to 0, while the configuration with the highest performance is assigned a score equal to 30. The scores of the intermediate packages linearly vary between the maximum and the minimum values, using the following equation 4 and 5 for summer and winter condition respectively:

$$SCORE_{cooling,i} = 30 \times \left(1 - \frac{x_{max} - \mathrm{x_i}}{\mathrm{x_{max}} - \mathrm{x_{min}}}\right) \quad (4)$$

$$SCORE_{heatingi} = 30 \times \frac{x_{max} - \mathrm{x_i}}{\mathrm{x_{max}} - \mathrm{x_{min}}} \quad (5)$$

where x_{max} e x_{min} are the maximum and minimum values of index considered (STR, ETR, TER), while x_i is the value obtained from the i-th green roof package in the specific index considered. Moreover, considering that, among the benefits examined of green roofs, the least important is the reduction in temperature fluctuations of the waterproof membrane, compared to the energy saving and the mitigation of the urban heat island, a maximum score of 6 points is assigned to value of the index TER for each green roof package analyzed. This means that TER index was characterized by a weight of 0.20 in comparison with the other two indexes.

This methodology allowed not only to identify the green roof packages with the highest energy performances, but also to take into account the real value obtained by each package in the used indexes. On the contrary, distributing the scores only on the basis of the position of each green roof package in the various indexes used would not have taken into account the real difference in the value of the indexes. Each plant-substrate configuration reaches a total score that is calculated summing the scores of the indexes, during both the heating and the cooling period.

Overall, each green roof "package" (substrate+plants) will be characterized by different performances in terms of energy saving, urban heat island mitigation and durability of roof materials. Therefore, a comparison among different green roof packages can be performed using a combination of the above performance indexes. Moreover, the analysis of each index provide information about specific energy performance. For example, it is possible to identify the green roof package that optimize the urban heat island mitigation considering the value obtained by each green roof configuration in the ETR index, in fact, the lower the surface temperatures the lower the overheating of the air in cities due to the surfaces of the building roofs.

To assess the influence of the different types of green roof on the daily trend of surface temperatures, representative days of the most severe climatic conditions were chosen, the summer day with the maximum air temperature of about 34 °C, 12th August, and the winter day with the minimum air temperature of about -2 °C, 29th January.

While it is advisable during summer to install plant species that reduce external surface temperatures in order to optimize energy performance, during winter it is preferable to adopt plant species that reach higher surface temperatures, in order to maximize the heat gain generated by direct solar radiation.

In the light of these considerations, during the summer period the maximum score was attributed to the green roof package with the lowest index values, while the minimum score was given to the green roof package characterized by the highest index values. The opposite criterion was used for the indexes assessing energy performance during the heating period Therefore, for each index, the score assigned to each green roof package depends on its rank within the thirty configurations tested. This methodology made it possible to identify the plant-substrate configurations that optimized the energy performance of the green roof.

3. RESULTS AND DISCUSSION

3.1 Green roofs with different plant species

A first group of simulations was conducted maintaining constant the thermo-physical properties of the substrate and varying the plant species used.

3.1.1 Internal and external surface temperature

In particular, Figure 1 shows the results of the internal and external surface temperatures of the test cell during the summer reference day. These results show that, with regard to external surface temperatures, Sedum and Sempervivum reach the highest temperatures, over 40°C, while Salvia reduces external surface temperatures to about 36°C. Heuchera Purple, Stachys and Heuchera yellow exhibit intermediate behavior.

The internal surface temperatures, on the other hand, do not depend greatly on the different plant species that constitute the green roofs, in fact in Figure 1 they are overlapped. This is due to the particular technical and constructive features of the envelope, characterized by high thermal insulation level and low thermal inertia (Table 1), and to the reduced size of the indoor environment. Indeed, internal surface temperatures are more affected by the thermo-physical properties of the test cell envelope, and especially by the thickness of the thermal insulation. The maximum surface internal temperatures, about 36°C, are reached at 4.00 p.m., with a delay of about three hours compared to the external surface temperature peak. This time delay, generally termed “thermal lag”, does not vary for the different plant species analyzed. Moreover, no significant difference among the external surface temperatures of the different plant species was observed at night.

Figure 2 shows the results of the surface temperatures for the selected reference day during the heating period (29th January). Compared to the results obtained on the summer day, the differences in the external surface temperature among the different plant species are less evident. Salvia is still the species with the lowest external surface temperatures, maximum 9.5° C, while Sempervivum and Sedum reach the highest temperatures, around 11° C.

As result, it is possible to point out that salvia is the plant with the lowest external surface temperatures while Sedum and Sempervivum are the plants with the highest external surface temperatures. This results is in agreement with the experimental tests performed in [30], where the authors investigated whether some plants can offer more potential summertime environmental cooling than others during the day. In particular, the authors found that Salvia or Stachys had the lowest external surface temperature, whereas Sempervivum had the highest differences between mean values during the monitoring period.

These results show that the major differences in terms of surface temperatures of the test cell are between Salvia and Sedum/Sempervivum. These differences are due to the specific features of the various plant species, set out in Table 3. In particular, Salvia is the plant species with the highest values for height, (0,475 m), LAI (5,00 m^2/m^2), leaf reflectivity (0,220) and minimum stomatal resistance (300 $mmol/m^2s$). Vice versa, Sedum and Sempervivum are the plants with the lowest values of these parameters, in particular being 0,125 and 0,050 m (height), 2,80 and 3,25 m^2/m^2 (LAI), 0,180 and 0,155 (leaf reflectivity), 105,0 $mmol/m^2s$ (minimum stomatal resistance), respectively.

All the green roof configurations permit a reduction in the external surface temperatures of over 40% compared to the bare roof, and all the minimum surface temperatures reached by the green roof types are over 30% higher than the bare roof temperatures. In particular, Salvia reduces the maximum and minimum surface temperatures compared to the bare roof by 46.22% and 31.79% respectively, and Sedum by 38.76% and 32.56% respectively.

Table 5 shows the variation between the maximum and minimum external surface temperatures (maximum daily temperature minus minimum daily temperature) reached during the summer reference day for the different types of green roof. The reduction in the percentage of the temperature fluctuations in comparison with the bare roof is also calculated. All the plant species were found to reduce temperature fluctuations between the minimum and maximum values by over 60%.

3.1.2 Annual energy consumption

Finally, Table 5 also shows the annual energy consumption of the bare roof and of the different types of green roof, and the annual energy saving of the various green roof types compared to the bare roof. The greater energy saving correspond to the lowest temperature fluctuations between maximum and minimum, as shown in Figure 1. Furthermore, by summing the cooling and heating energy saving in Table 5, is demonstrated that in Mediterranean climate, the highest energy savings are reached by choosing the vegetation with the highest energy performance during the summer, such as Salvia and not the Succulent plants (i.e. Sedum and Sempervivum), enhancing the energy performance during the heating period.

In particular, in accordance with the findings for surface temperatures, Sedum reduces energy consumption during winter by 8.41% compared to the bare roof, while Salvia maximizes energy saving during summer by 23.53% compared to the bare roof.

The results found, both for surface temperatures and for energy saving, show that, with reference to the specific climatic conditions of the Mediterranean area, Salvia is the plant species with the highest energy performance while Sedum and Sempervivum, widely used in northern European regions, are characterized by the lowest energy performance.

3.2 Performance evaluation

In this section of the study, the performances of 30 configurations of green roofs deriving from the combination of the different plant species and substrates are evaluated.

3.2.1 STR, ETR and TER indexes

Figure 3 shows the STR_{av} index, while Figure 4 depicts ETR_{max} index for the different plant species and substrates analyzed during the summer and winter reference day.

Since these indexes are a function of the external surface temperature, during the summer season, the lower their value, the higher the energy performance of the plant-substrate configuration used.

During summer, all the types of green roof achieve STR_{av} values lower than 1.0, signifying that both maximum and average external surface temperatures are lower than those of the bare roof. The values of STR_{av} range from 0.854 to 0.928. The values of ETR_{max}, on the other hand, are constantly higher than 1.0, from 1.175 to 1.455; this denotes that all the plant-substrate configurations reach surface temperatures higher than the outside air temperature. Furthermore, the greater variability of the ETR_{max} shows that the proper chose of the green roof package can affect mainly this index.

Regarding these two indexes, the green roofs packages that involve Salvia achieve the best performances during summer (lowest index values), regardless of the type of substrate coupled with them. Stachys and Heuchera purple attain a slightly lower energy performance than Salvia. Among the different soil layers inspected, the green roofs that include Substrate 3 allow to attain the best performances (lowest index values).Furthermore, the combination of Heuchera yellow with the Substrate 5 present high performance compared to Heuchera yellow with the other substrate, during both winter and summer. During winter, Sedum and Sempervivum present the best energy performance when they are combined with Substrate 1, 2, 4 and 5 and not with Substrate 3 that enhance the cooling energy performance of all the green roof packages. These considerations highlight the importance to choose the proper substrate during the design stage of the green roof.

ETR_{max} depends more on the substrate type than STR_{av}. Heuchera purple and Stachys are characterized by a lower energy performance than Salvia during summer; however, when joined with Substrate 3, they achieve values of 1.208 and 1.219 respectively for ETR_{max}, that are lower than some configurations using Salvia as plant species. Similarly, Sempervivum, which is generally characterized by a lower performance during winter compared to Sedum, has a higher energy performance than Sedum when combined with substrate 5, except when Sedum is used with Substrate 5.

Unlike the summer period, during winter the higher the index values, the better the energy performance of the different plant-substrate configurations. Even during the winter period, STR_{av} attains values lower than 1.0, signifying external surface temperatures lower than those of the bare roof. The plant-substrate configurations perform in a similar way for the winter season as for the summer one. Salvia confirms to be the plant with the lowest index values while Sedum is the plant that attains the highest index values, therefore Sedum allows to achieve the better energy performance during the heating period. The different configurations show significant variations on the index values. In this way, the plant-substrate configuration that optimizes the energy performance of the green roof during the winter season is pointed out, i.e. Sedum and Sempervivum, regardless of the substrate type used.

Finally, in Figure 5, the TER index is shown for the summer and winter days respectively. All the analyzed plant-substrate configurations allow the reduction in temperature fluctuations compared to the bare roof. In particular, during the summer cooling period, TER varies between 0.316 and 0.507, while during the winter period it is between 0.304 and 0.571.

The considerations drawn for the previous indexes apply also to the TER indexes. In particular, the TER values are affected by the substrate and vary in a fairly continuous way in the cooling period.

3.2.2 Comparison of indexes results with previous research

Bevilacqua et al. [32] used the previously defined indexes for a very concise description of the surface thermal behavior of the investigated green and traditional roof and for an immediate comparison between them. Therefore, a comparison between the results obtained is carried out.

In [32], STR_{av} varied between 0.72 and 0.92 and between 0.8 and 1.10 during summer and winter period, respectively. In this study it varied from 0.85 and 0.93 during the summer and between 0.70 and 1.0 during winter period.

Concerning ETR_{max}, in [32] it was found varying between 1.08 and 1.17 and between 1.0 and 2.40 during summer and winter period, respectively. In the present research, this index varied from 1.17 to 1.45 during the summer period and from 0.95 and 1.70.

Finally, TER index varied between 0.46 and 0.53 during summer and between 0.43 and 0.61 during winter, in the previous study [32] while in this research it varied from 0.33 to 0.51 and from 0.31 to 0.57.

As this comparison shown, the values of the different index are close to that one obtained by the previous study. However, the aforementioned indexes were evaluated at a monthly level in [32] while, in this study, the indexes are shown daily for the extreme climatic conditions during both summer and winter period, thus, the climatic conditions are different.

3.2.3 Ranking results

To compare the energy performance of the various plant-substrate configurations, a ranking was developed summing the scores obtained for each of the above-mentioned indexes, during both the heating and the cooling period. The results are reported in Table 6. In particular, the plant-substrate configurations with the best energy performance are Sempervivum with Substrate 5 (69.62 points), Salvia with Substrate 3 (68.67 points) and Heuchera yellow with Substrate 5 (66.66 points).

In addition, the data in Table 6 offer further useful information related to the ability of each package to perform better during the winter or the summer period. With this aim, the cells in Table 6 are highlighted with different colors. Specifically, the packages with the better performances during the summer period are highlighted in blue, while the packages with the better performance during the winter period are colored in red. Packages with medium performances both in winter and summer are highlighted in green, range 24-20. The packages with acceptable performances are highlighted in orange, range 19-15. As an example, when the performance during the cooling period would be emphasized, the plant species with the highest energy performance proves to be Salvia, which does not have adequate thermo-physical properties during the heating period. Furthermore, Heuchera purple and Stachys are characterized by medium-high performance during the cooling period. Otherwise, Sempervivum and Sedum guarantee the highest performance during the winter period. Finally, Heuchera yellow provide more balanced performances during both the heating and the cooling period.

It is interesting to highlight the role of the characteristics of the substrate on the energy performance of the green roof. The prominence of substrate is confirmed observing that the best configurations adopt Substrate 5 when used with Sedum and Sempervivum and Substrate 3 when used with Salvia and Heuchera yellow. As a result, the substrate and vegetation selection are strictly correlated. In addition, the same plant species combined with different substrate types attain heterogeneous performances.

4. CONCLUSION AND FUTURE WORK

The present study assessed the effect of the plant-substrate combination on the energy performance of the green roof using realistic values to characterize the vegetation and substrate. The methodology defined consists in the comparison among 30 different green roof types by means of indexes that made it possible to identify the green roof packages with the highest energy performance and a ranking was developed summing the scores obtained for each of the indexes. These indexes are used to characterize the behavior of the green roof in relation to the urban heat island phenomenon, energy saving and temperature fluctuations on the waterproof membrane.

The analysis developed highlights Salvia as the plant species with the highest ranking during the summer period in Mediterranean climate, due to the highest values for height, (0,475 m), LAI (5,00 m^2/m^2), leaf reflectivity (0,220) and minimum stomatal resistance (300 $mmol/m^2s$).

However, in Mediterranean, succulent plants such as Sedum and Sempervivum, widely used in green roofs, provide the best ranking when an all year around performance are taken into account. Heuchera purple, Heuchera yellow and Stachys exhibit a lower energy performance than the other plant species analyzed. Finally, it was found that the performance of green roofs depends largely on the thermo-physical properties of the substrate used. In fact, the same plant species combined with different substrate types attain heterogeneous performances.

The proposed study made it possible to identify among the 30 plant-substrate configurations which one that optimized the energy performance of the green roof in Mediterranean climate.

Researchers and designers could apply the same methodology to evaluate the energy performance of green roof on different climatic conditions and identifying which green roof packages offer the highest performance. In fact, the climatic conditions affect the energy performance of green roof, thus other substrate-plants combinations could enhance green roof performance in other climatic conditions, whether are dominant heating or cooling periods. The indexes and methodology proposed for comparing the performance of different green roof packages have a general validity, therefore, it can be applied to different climates.

Further analysis may be carried out for investigated the performance of additional substrate types and plant species for which thermal and physical parameters determined through experimental set-up have to be used. Furthermore, a field for future experimental and simulation could be the insertion of "innovative" materials in the green roof package, e.g. products derived from waste or recycling processes. In addition, future research need to include the drainage and filter layers in the simulations.

Acknowledgements

This research was funded by "the Notice 5/2016 for financing the Ph.D. regional grant in Sicily" as part of the Operational Program of European Social Funding 2014–2020 (PO FSE 2014–2020).

References

[1] M. Santamouris, Regulating the damaged thermostat of the cities - Status, impacts and mitigation challenges, Energy Build. 91 (2015) 43–56. doi:10.1016/j.enbuild.2015.01.027.

[2] H. Akbari, C. Cartalis, D. Kolokotsa, A. Muscio, A.L. Pisello, F. Rossi, M. Santamouris, A. Synnefa, N.H. Wong, M. Zinzi, Local climate change and urban heat island mitigation techniques – the state of the art, J. Civ. Eng. Manag. 22 (2016) 1–16. doi:10.3846/13923730.2015.1111934.

[3] G. Pérez, A. Vila, L. Rincón, C. Solé, L.F. Cabeza, Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material, Build. Environ. 97 (2012) 347–354. doi:10.1016/j.apenergy.2011.11.051.

[4] S. Cascone, F. Catania, A. Gagliano, G. Sciuto, Energy performance and environmental and economic assessment of the platform frame system with compressed straw, Energy Build. 166 (2018) 83–92. doi:10.1016/j.enbuild.2018.01.035.

[5] H. Akbari, L.S. Rose, H. Taha, Analyzing the land cover of an urban environment using high-resolution orthophotos, Landsc. Urban Plan. 63 (2003) 1–14. doi:10.1016/S0169-2046(02)00165-2.

[6] E. Ng, L. Chen, Y. Wang, C. Yuan, A study on the cooling effects of greening in a high-density city: An experience from Hong Kong, Build. Environ. 47 (2012) 256–271. doi:10.1016/j.buildenv.2011.07.014.

[7] A.L. Pisello, C. Piselli, F. Cotana, Thermal-physics and energy performance of an innovative green roof system: The Cool-Green Roof, Sol. Energy. 116 (2015) 337–356. doi:10.1016/j.solener.2015.03.049.

[8] V.W.Y. Tam, J. Wang, K.N. Le, Thermal insulation and cost effectiveness of green-roof systems: An empirical study in Hong Kong, Build. Environ. 110 (2016) 46–54. doi:10.1016/j.buildenv.2016.09.032.

[9] M. D'Orazio, C. Di Perna, E. Di Giuseppe, Green roof yearly performance: A case study in a highly insulated building under temperate climate, Energy Build. 55 (2012) 439–

451. doi:10.1016/j.enbuild.2012.09.009.

[10] P. Bevilacqua, D. Mazzeo, N. Arcuri, Thermal inertia assessment of an experimental extensive green roof in summer conditions, Build. Environ. 131 (2018) 264–276. doi:10.1016/j.buildenv.2017.11.033.

[11] Y. Tian, X. Bai, B. Qi, L. Sun, Study on heat fluxes of green roofs based on an improved heat and mass transfer model, Energy Build. 152 (2017) 175–184. doi:10.1016/j.enbuild.2017.07.021.

[12] F. Olivieri, C. Di Perna, M. D’Orazio, L. Olivieri, J. Neila, Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a Mediterranean coastal climate, Energy Build. 63 (2013) 1–14. doi:10.1016/j.enbuild.2013.03.054.

[13] J. Coma, G. Pérez, C. Solé, A. Castell, L.F. Cabeza, Thermal assessment of extensive green roofs as passive tool for energy savings in buildings, Renew. Energy. 85 (2016) 1106–1115. doi:10.1016/j.renene.2015.07.074.

[14] F. Ascione, N. Bianco, F. de’ Rossi, G. Turni, G.P. Vanoli, Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning?, Appl. Energy. 104 (2013) 845–859. doi:10.1016/j.apenergy.2012.11.068.

[15] H.F. Castleton, V. Stovin, S.B.M. Beck, J.B. Davison, Green roofs; Building energy savings and the potential for retrofit, Energy Build. 42 (2010) 1582–1591. doi:10.1016/j.enbuild.2010.05.004.

[16] S. Cascone, F. Catania, A. Gagliano, G. Sciuto, A comprehensive study on green roof performance for retrofitting existing buildings, Build. Environ. 136 (2018) 227–239. doi:10.1016/j.buildenv.2018.03.052.

[17] J. Czemiel Berndtsson, Green roof performance towards management of runoff water quantity and quality: A review, Ecol. Eng. 36 (2010) 351–360. doi:10.1016/j.ecoleng.2009.12.014.

[18] J.C. Berndtsson, L. Bengtsson, K. Jinno, Runoff water quality from intensive and extensive vegetated roofs, Ecol. Eng. 35 (2009) 369–380.

doi:10.1016/j.ecoleng.2008.09.020.

[19] J. Mentens, D. Raes, M. Hermy, Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?, Landsc. Urban Plan. 77 (2006) 217–226. doi:10.1016/j.landurbplan.2005.02.010.

[20] J. Li, O.W.H. Wai, Y.S. Li, J. Zhan, Y.A. Ho, J. Li, E. Lam, Effect of green roof on ambient CO2 concentration, Build. Environ. 45 (2010) 2644–2651. doi:10.1016/j.buildenv.2010.05.025.

[21] F. Madre, A. Vergnes, N. Machon, P. Clergeau, A comparison of 3 types of green roof as habitats for arthropods, Ecol. Eng. 57 (2013) 109–117. doi:10.1016/j.ecoleng.2013.04.029.

[22] D. Kolokotsa, M. Santamouris, S.C. Zerefos, Green and cool roofs' urban heat island mitigation potential in European climates for office buildings under free floating conditions, Sol. Energy. 95 (2013) 118–130. doi:10.1016/j.solener.2013.06.001.

[23] M. Santamouris, Cooling the cities - A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, Sol. Energy. 103 (2014) 682–703. doi:10.1016/j.solener.2012.07.003.

[24] Y. Wang, U. Berardi, H. Akbari, Comparing the effects of urban heat island mitigation strategies for Toronto, Canada, Energy Build. 114 (2016) 2–19. doi:10.1016/j.enbuild.2015.06.046.

[25] M. Zinzi, S. Agnoli, Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region, Energy Build. 55 (2012) 66–76. doi:10.1016/j.enbuild.2011.09.024.

[26] S. Vera, C. Pinto, P.C. Tabares-Velasco, W. Bustamante, F. Victorero, J. Gironás, C.A. Bonilla, Influence of vegetation, substrate, and thermal insulation of an extensive vegetated roof on the thermal performance of retail stores in semiarid and marine climates, Energy Build. 146 (2017) 312–321. doi:10.1016/j.enbuild.2017.04.037.

[27] C. Zeng, X. Bai, L. Sun, Y. Zhang, Y. Yuan, Optimal parameters of green roofs in

representative cities of four climate zones in China: A simulation study, Energy Build. 150 (2017) 118–131. doi:10.1016/j.enbuild.2017.05.079.

[28] G. Peri, G. Rizzo, G. Scaccianoce, M. La Gennusa, P. Jones, Vegetation and soil – related parameters for computing solar radiation exchanges within green roofs: Are the available values adequate for an easy modeling of their thermal behavior?, Energy Build. 129 (2016) 535–548. doi:10.1016/j.enbuild.2016.08.018.

[29] J. Coma, A. de Gracia, M. Chàfer, G. Pérez, L.F. Cabeza, Thermal characterization of different substrates under dried conditions for extensive green roofs, Energy Build. 144 (2017) 175–180. doi:10.1016/j.enbuild.2017.03.031.

[30] M. Vaz Monteiro, T. Blanuša, A. Verhoef, M. Richardson, P. Hadley, R.W.F. Cameron, Functional green roofs: Importance of plant choice in maximising summertime environmental cooling and substrate insulation potential, Energy Build. 141 (2017) 56–68. doi:10.1016/j.enbuild.2017.02.011.

[31] Y. He, H. Yu, A. Ozaki, N. Dong, S. Zheng, Long-term thermal performance evaluation of green roof system based on two new indexes: A case study in Shanghai area, Build. Environ. 120 (2017) 13–28. doi:10.1016/j.buildenv.2017.04.001.

[32] P. Bevilacqua, D. Mazzeo, R. Bruno, N. Arcuri, Surface temperature analysis of an extensive green roof for the mitigation of urban heat island in southern mediterranean climate, Energy Build. 150 (2017) 318–327. doi:10.1016/j.enbuild.2017.05.081.

[33] A. Gagliano, M. Detommaso, F. Nocera, G. Evola, A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs, Build. Environ. 90 (2015) 71–81. doi:10.1016/j.buildenv.2015.02.043.

[34] S. Ulubeyli, V. Arslan, Economic viability of extensive green roofs through scenario and sensitivity analyses: Clients' perspective, Energy Build. 139 (2017) 314–325. doi:10.1016/j.enbuild.2017.01.042.

[35] M.M. Liu, Probabilistic prediction of green roof energy performance under parameter uncertainty, Energy. 77 (2014) 667–674. doi:10.1016/j.energy.2014.09.043.

[36] D. Yeom, P. La Roche, Investigation on the cooling performance of a green roof with a

radiant cooling system, Energy Build. 149 (2017) 26–37. doi:10.1016/j.enbuild.2017.05.035.

[37] U. Berardi, P. La Roche, J.M. Almodovar, Water-to-air-heat exchanger and indirect evaporative cooling in buildings with green roofs, Energy Build. 151 (2017) 406–417. doi:10.1016/j.enbuild.2017.06.065.

[38] K. Vijayaraghavan, Green roofs: A critical review on the role of components, benefits, limitations and trends, Renew. Sustain. Energy Rev. 57 (2016) 740–752. doi:10.1016/j.rser.2015.12.119.

[39] A. Teemusk, Ü. Mander, Greenroof potential to reduce temperature fluctuations of a roof membrane: A case study from Estonia, Build. Environ. 44 (2009) 643–650. doi:10.1016/j.buildenv.2008.05.011.

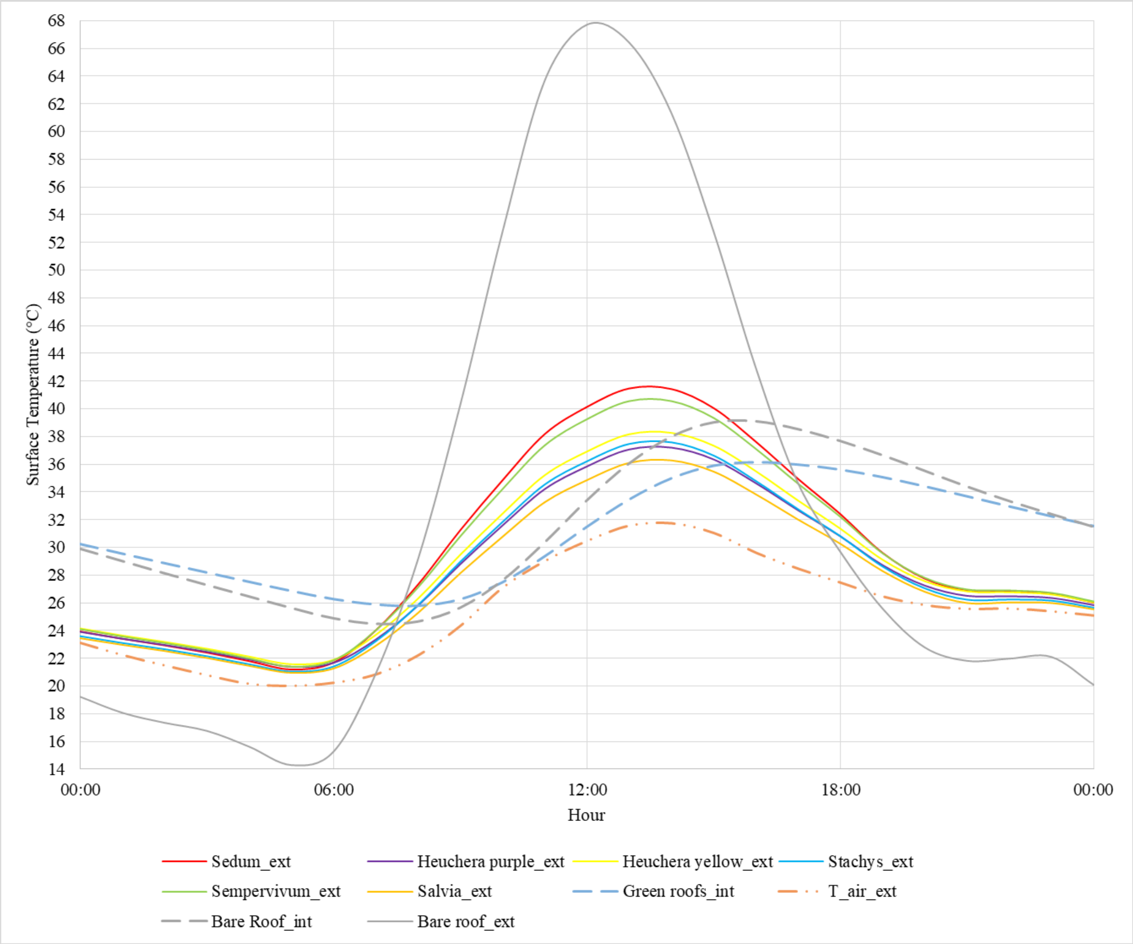

Figure 1 Internal and external surface temperatures of the test cell during the reference day in August

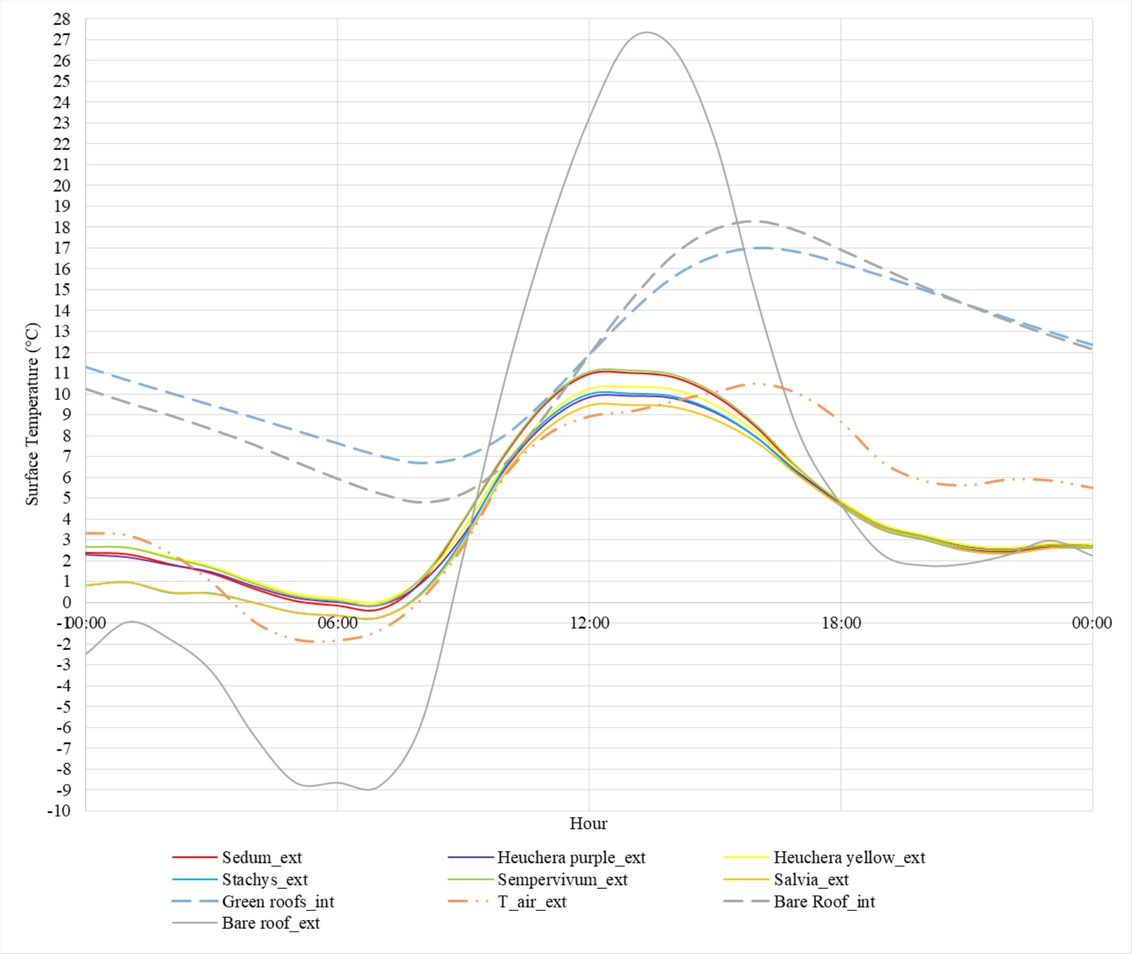

Figure 2 Internal and external surface temperatures of the test cell during the reference day in January

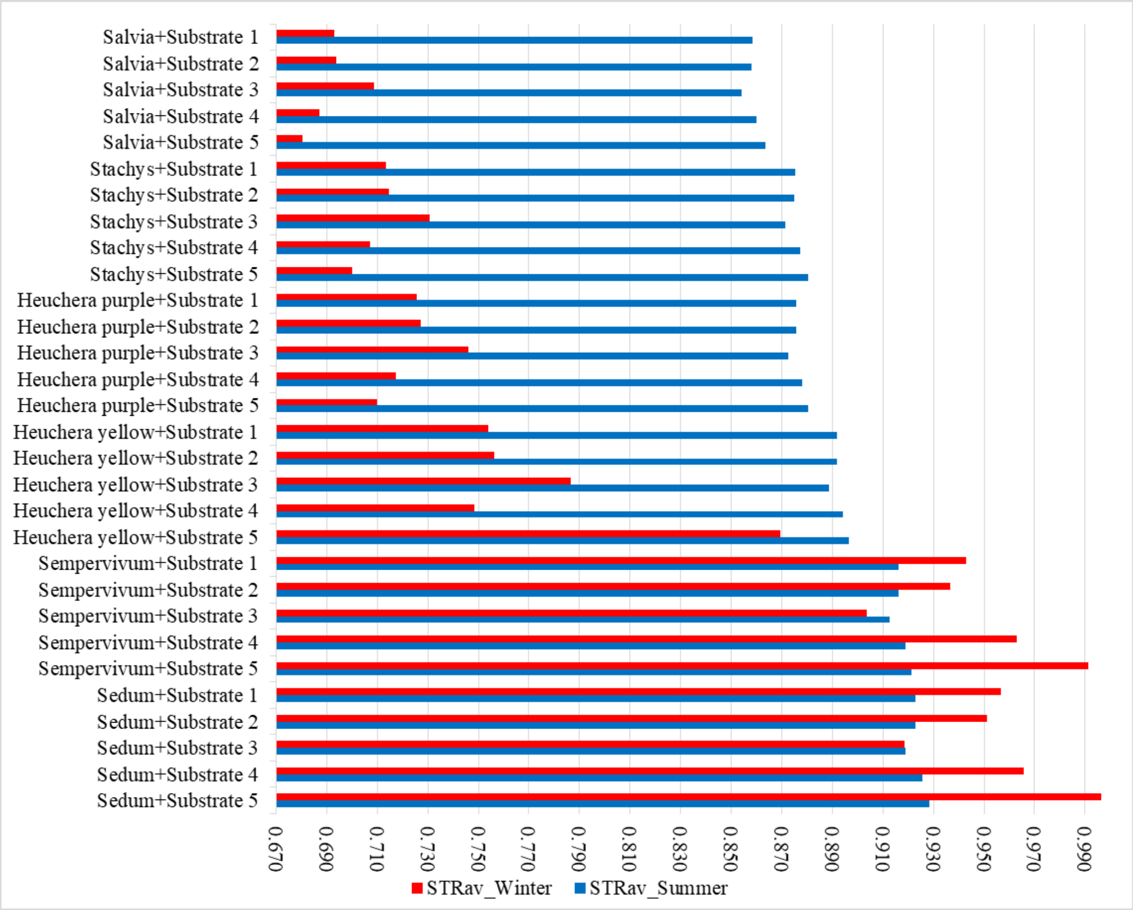

Figure 3. STR_{av} index in the summer and winter reference day for different green roof packages

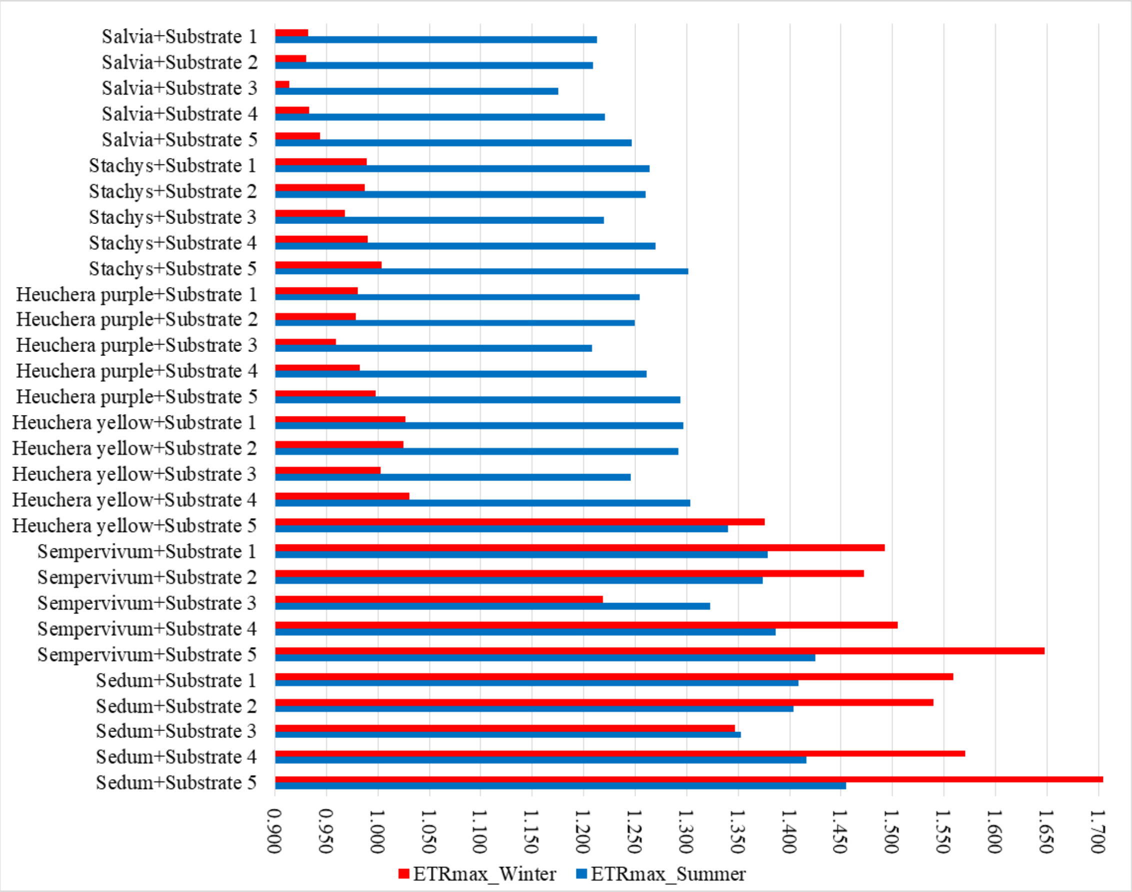

Figure 4. ETR$_{max}$ index in the summer and winter reference day for the different green roof packages

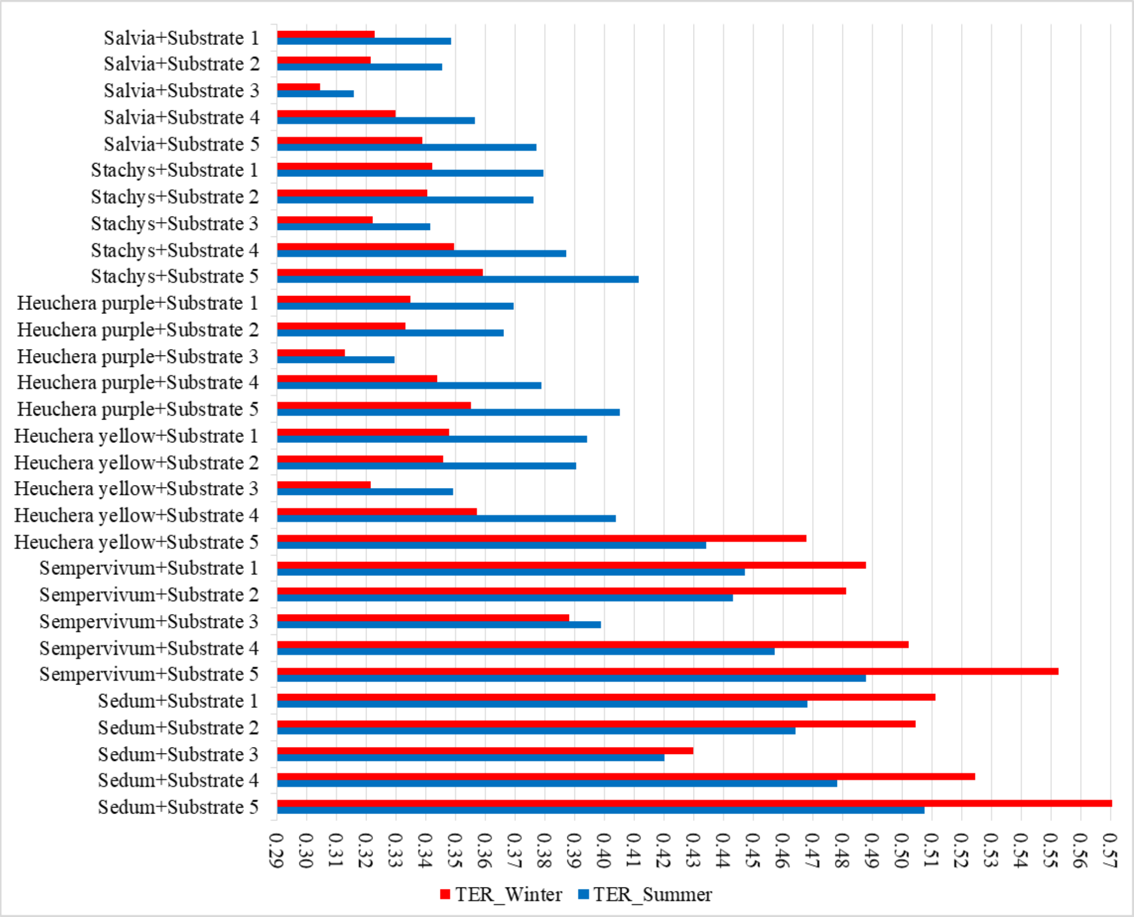

Figure 5. TER index in the summer and winter reference day for the different green roof packages

Table 1. Wall and Bare Roof section of test cell

Wall							
	Drywall	Glass Wool	OSB	Vapor Barrier	XPS	Air Space	Plywood
s [mm]	10.0	89.0	11.0	0.50	51.0	13.0	5.0
λ [W/mK]	0.180	0.044	0.130	-	0.043	0.079	0.130
ρ $[kg/m^3]$	950.0	12.0	650.0	-	35.0	1.23	560.0
Cp [J/kgK]	840.0	840.0	1700.0	-	1400.0	1000.0	2500.0
Bare Roof							
	Metal Sheet	Water Membrane	OSB	Air Space	XPS	Drywall	-
s [mm]	1.0	1.0	11.0	38.0	140.0	11.0	-
λ [W/mK]	44.000	0.210	0.130	0.233	0.0430	0.1800	-
ρ $[kg/m^3]$	7824.0	1300.0	650.0	1.23	35.0	950.0	-
Cp [J/kgK]	500.0	1800.0	1700.0	1000.0	1400.0	840.0	-

Table 2. U-value of the test cell envelope

	Wall	Window	Bare roof	Floor
U-value $[W/m^2K]$	0.308	1.960	0.306	0.299

Table 3. Plant parameters utilized [30]

Plant species	Height of plants [m]	LAI $[m^2/m^2]$	Leaf reflectivity -	Leaf emissivity -	Stomatal resistance $[mmol/m^2s]$
Sedum mix*	0.125	2.80	0.180	0.97	105.0
Heuchera “Obsidian” Purple	0.250	5.00	0.200	0.97	170.0
Heuchera “Electra” Yellow	0.150	4.50	0.205	0.97	195.0
Stachys byzantina	0.375	4.25	0.195	0.97	255.0
Sempervivum “Reinhard”	0.050	3.25	0.155	0.97	105.0
Salvia officinalis “Berggarten”	0.475	5.00	0.220	0.97	300.0

* A mat of Sedum species used as an industry standard

Table 4. Substrate parameters utilized and composition [29]

Sample identifier	Coco peat %	Compost %	Crushed wastes %	Sand %	Pozzolana %	Conductivity [W/mK]	Density [Kg/m^3]	Specific heat [J/kgK]
Substrate 1	0	40	0	20	40	0.2	873.2	788
Substrate 2	25	25	40	10	0	0.21	759.6	923
Substrate 3	N/A	6	N/A	N/A	N/A	0.284	772.7	1360
Substrate 4	25	40	30	5	0	0.288	748.4	546
Substrate 5	60	15	20	5	0	0.229	724	375

Table 5. Surface temperature comparison and annual energy consumption and saving of bare roof and green roof compared during summer and winter period

Roof type	T_{ext_max}-T_{ext_min} [°C]	Δ [%]	T_{ext_max}-T_{ext_min} [°C]	Δ [%]	Cooling energy consumption [Wh/m^2]	Cooling energy saving [%]	Heating energy consumption [Wh/m^2]	Heating energy saving [%]
Bare roof	53.42	-	35.87	-	43606	-	49860	-
Sedum	20.28	62.05	11.34	68.38	34603	20.65	45668	8.41
Heuchera purple	15.81	70.4	10.04	72.02	33761	22.58	46214	7.31
Heuchera yellow	16.69	68.75	10.3	71.27	34126	21.74	45991	7.76
Stachys	16.54	69.04	10.75	70.03	33621	22.9	46363	7.01
Sempervivum	19.16	64.14	11.23	68.7	34583	20.69	45674	8.4
Salvia	15.33	71.31	10.18	71.61	33345	23.53	46529	6.68

Table 6. Results of the effect of the different plant-substrate configurations on the energy performance of green roofs

Legend	25-30 High Cooling		25-30 High Heating		20-25 Medium-high		15-20 Medium	
Green roof Package	STR$_{av}$ Cooling	STR$_{av}$ Heating	ETR$_{max}$ Cooling	ETR$_{max}$ Heating	TER Cooling	TER Heating	**Score**	**Rank**
Salvia + Substrate 1	28.23	1.19	25.91	0.70	4.97	0.41	**61.41**	**13**
Salvia + Substrate 2	28.40	1.27	26.32	0.64	5.07	0.38	**62.08**	**12**
Salvia + Substrate 3	30.00	2.67	30.00	0.00	6.00	0.00	**68.67**	**2**
Salvia + Substrate 4	27.65	0.61	25.11	0.72	4.72	0.57	**59.37**	**15**
Salvia + Substrate 5	26.29	0.00	22.31	1.15	4.08	0.77	**54.60**	**20**
Stachys + Substrate 1	21.40	3.12	20.46	2.85	4.00	0.85	**52.68**	**23**
Stachys + Substrate 2	21.55	3.22	20.91	2.78	4.10	0.82	**53.38**	**22**
Stachys + Substrate 3	23.12	4.78	25.23	2.06	5.19	0.40	**60.78**	**14**
Stachys + Substrate 4	20.68	2.52	19.82	2.88	3.76	1.02	**50.67**	**25**
Stachys + Substrate 5	19.34	1.85	16.45	3.39	3.00	1.24	**45.26**	**30**
Heuchera purple + Substrate 1	21.24	4.29	21.53	2.54	4.31	0.69	**54.60**	**21**
Heuchera purple + Substrate 2	21.35	4.42	21.99	2.45	4.42	0.65	**55.29**	**19**
Heuchera purple + Substrate 3	22.65	6.23	26.40	1.71	5.57	0.19	**62.75**	**11**
Heuchera purple + Substrate 4	20.34	3.51	20.72	2.59	4.02	0.89	**52.07**	**24**
Heuchera purple + Substrate 5	19.34	2.78	17.28	3.19	3.20	1.15	**46.94**	**28**
Heuchera yellow + Substrate 1	14.76	6.98	16.95	4.30	3.54	0.98	**47.51**	**27**
Heuchera yellow + Substrate 2	14.86	7.19	17.46	4.23	3.66	0.93	**48.33**	**26**
Heuchera yellow + Substrate 3	16.10	10.06	22.44	3.39	4.95	0.38	**57.32**	**18**
Heuchera yellow + Substrate 4	13.77	6.45	16.20	4.42	3.24	1.19	**45.27**	**29**
Heuchera yellow + Substrate 5	12.92	17.96	12.27	17.54	2.29	3.68	**66.66**	**3**
Sempervivum + Substrate 1	4.85	24.93	8.15	21.94	1.88	4.13	**65.89**	**6**
Sempervivum + Substrate 2	4.96	24.35	8.67	21.19	2.01	3.98	**65.16**	**7**
Sempervivum + Substrate 3	6.31	21.20	14.20	11.55	3.40	1.88	**58.53**	**17**
Sempervivum + Substrate 4	3.84	26.83	7.38	22.41	1.57	4.46	**66.49**	**4**
Sempervivum + Substrate 5	2.83	29.53	3.21	27.85	0.61	5.59	**69.62**	**1**
Sedum + Substrate 1	2.15	26.25	4.92	24.47	1.23	4.66	**63.69**	**8**
Sedum + Substrate 2	2.28	25.70	5.44	23.75	1.35	4.51	**63.04**	**10**
Sedum + Substrate 3	3.76	22.61	10.99	16.43	2.73	2.82	**59.34**	**16**
Sedum + Substrate 4	1.18	27.12	4.10	24.90	0.92	4.96	**63.19**	**9**
Sedum + Substrate 5	0.00	30.00	0.00	30.00	0.00	6.00	**66.00**	**5**