Thermal Characterization of Single Greening Components and Green Roofs

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Abstract

The aim of the project is to develop and evaluate measurement methods for the thermal characteristics of green roof and façade systems and their individual parts. These measurement methods provide a scientifically sound basis for the development of industrial standards for the physical characterization of such components and systems. A large number of measurements were carried out in the laboratory on plants, substrates and system structures to characterize their physical parameters, evaporation performance, effective thermal conductivity, heat capacity and heat transfer coefficient. In addition, various roof and façade greening systems were measured outdoors under real conditions. The results for green roof systems are presented in this paper.

Keywords: green roofs, thermal behavior, heat flux, evaporation, cooling, retention

1. Introduction

Green roofs improve the quality of stay and surroundings, balance the temperature in buildings and improve air quality in inner-city areas. In addition to these benefits, they also help to avoid heat islands and contribute to cooling the building in the summer months through shading and evaporation, furthermore there is an insulating effect in winter time.

The study from (Ketut Acwin Dwijendra et al., 2023) is based on simulations and compared the thermal performance of roof coverings in non-insulated and insulated buildings across climates in Medan, Indonesia; Najaf, Iraq; and Moscow, Russia. Green roofs significantly reduce cooling loads in hot humid environments, cutting energy demand by 31 %, and lower heating loads by up to 71 % due to increased thermal resistance. Green roofs are less effective in dry climates. Insulation reduces energy consumption for cooling but increases air conditioning operation at night.

A very good overview of "The effectiveness of green roofs in reducing building energy consumptions across different climates" is provided by the literature study by Bevilacqua (Bevilacqua, 2021) with a summary of 121 literature sources. Besir (Besir and Cuce, 2018) provides a comprehensive review of roof and façade greening with 157 literature sources. For mediterranean climates, Koroxenidis (Koroxenidis and Theodosiou, 2021) carries out a comprehensive energy demand analysis, the results of which are incorporated into an environmental life cycle analysis and an economic life cycle analysis in order to compare and evaluate two different green roofs with a conventional roof. In a study by Yang (Yang et al., 2021), measurements of a green roof at the Onondaga County Convention Center in Syracuse (USA) for both summer and winter conditions are compared with simulations which consider both energy and water balancing to describe the thermal dynamic behaviour of the green roof. Bevilacqua (Bevilacqua et al., 2020) calculates the temperatures and heat flows of an extensive green roof on a real building at the University of Calabria (Italy) using the transient dynamic code TRNSYS and compares these results with real experimental data from 2016 and 2017.The measurements of the year-round energy balance of an existing green roof and an ungreened reference roof in Italy are compared with simulations using a Finite Element Model (FEM) code for obtaining equivalent thermophysical properties (Guattari et al., 2020). In a living laboratory in Italy, lightweight extensive green roof for building renovation is being investigated for different roof orientations and sky orientations for the summer case (Salvalai et al., 2023). Schade (Schade et al., 2021) measured the performance of a green roof compared with a black roof on a highly insulated building in a subarctic climate in Kiruna, Sweden. Yildirim (Yıldırım et al., 2023) measures the temperature curves over a year for three differently planted roof structures on the island of Cyprus in Nicosia (TRNC). Richter and Dickhaut (Richter and Dickhaut, 2023) investigated various blue-green roofs in Hamburg and compared the hydrological effectiveness of retention roofs with extensive green roofs without rainwater retention and established the positive effect on both the vegetation and the evaporation

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capacity.

Previous studies of green roofs and façades have mostly been based on individual cases only. In order to move away from individual case studies or simulations and to be able to make a comprehensive statement about the thermal effect of green roofs and façades on buildings, the U-green project was launched. As part of the public-funded research project U-green, commercially available roof and façade greening systems are systematized into classes and both the individual components and the overall systems are thermally characterized. The project contributes to the holistic recording of all thermal effects of greening systems. In particular, the dynamic thermal behavior of façade and roof greening systems is to be considered. This opens up the possibility of reliably determining the thermal insulation effect and evaporative cooling performance of greening components and systems. The transpiration performance of different plants and the stationary and dynamic thermal behavior of green roofs and façades are also analyzed. Overall, this results in a register of measurement data that is published online without barriers and thus made freely accessible to the interested public.

For this purpose, a large number of different laboratory measurements as well as measurements in the field are carried out. This paper presents results of various laboratory measurements on substrates for green roofs and, in addition, outdoor measurements on six different roof structures.

2. Laboratory Measurements

2.1 Plant transpiration

In order to ensure a holistic recording of the thermal processes in the various greening systems and to establish a comprehensive data basis, we measured the transpiration rate of a number of different plants under defined conditions in a climate chamber. For this purpose, the different plants were each placed in three pots on a scale in the climate chamber with three lamps, whose spectrum is specially designed for plants, type DL2 from RVG LICHT. The substrate was covered with foil so that only the transpiration of the plants themselves was determined. The temperature was set to 25 °C, the humidity to 50 % and the illumination intensity to 70 kLux (center area). The measurements were taken under water saturation. The measurement setup is shown in Figure 1.

Fig. 1: Measurement setup in the climate chamber to determine the transpiration of different plants. The plants were placed on a scale and illuminated with three lamps, whose spectrum is specially designed for plants, type DL2 from RVG LICHT.

Figure 2 shows the transpiration rates of the plants used in the green roof systems for the outdoor measurements (see section 3).

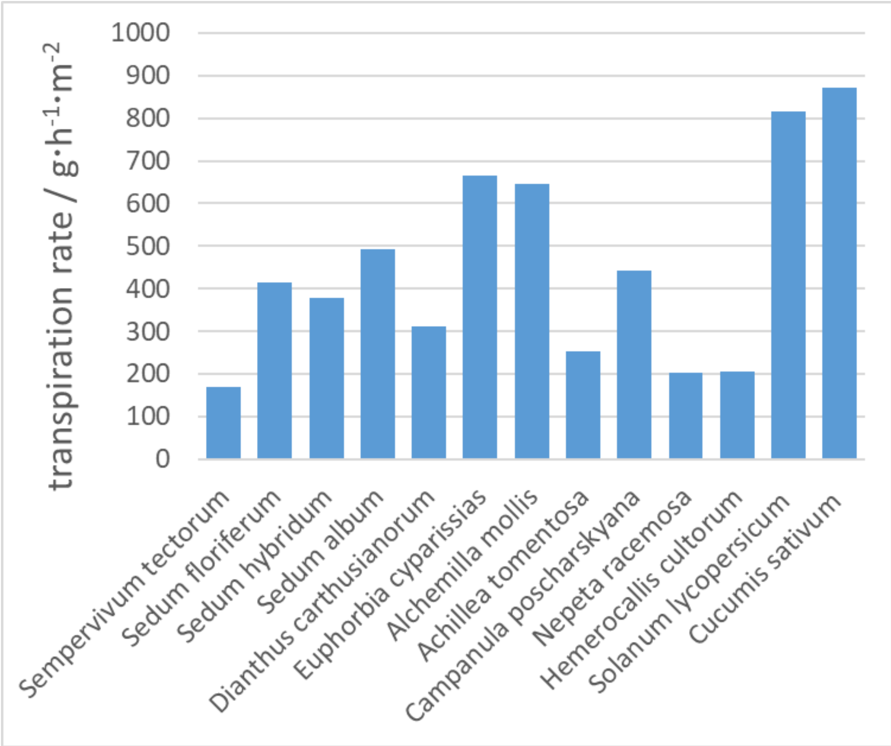

Fig. 2: Measured transpiration rate per ground area of different plants typically used in the green roof systems.

2.2 Moisture-dependent heat capacity and thermal conductivity of substrates for greening systems

In addition, the heat capacity and thermal conductivity of different substrates were measured as a function of water content.

The resulting heat capacity and effective thermal conductivity of three different roof substrates as a function of water content are shown in Figure 3. The measurements show the typical linear increase in heat capacity with increasing water content. The effective thermal conductivities show the typical S-shaped curves with a slow increase for low water contents, an extensive linear range, and a saturation range for high water contents. Measurement data for the Optigrün substrate are still pending. The substrates are used in the green roof systems for the outdoor measurements.

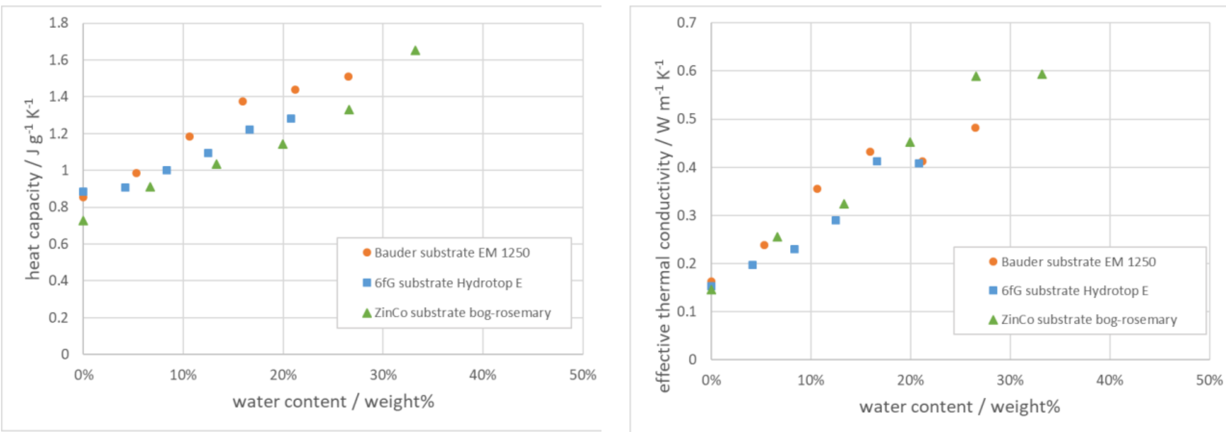

Fig. 3: Thermal heat capacity and effective thermal conductivity as a function of water content for three different green roof substrates: Bauder substrate EM 1250; 6 fürs Grün substrate Hydrotop E; ZinCo substrate bog-rosemary.

3. Outdoor Measurements

3.1 Measurement setup

Six different roof structures were installed in the open field next to the CAE institute building in Würzburg (Germany). Each roof structure is located in an inner box with an area of 120 cm x 100 cm, which is surrounded by a thermally insulated and weatherproof outer box for thermal separation and weather protection. The inner box is placed on load cells to record the evapotranspiration rate. The area below the inner box is temperature-controlled and reproduces the conditions that would occur in a room below the roof structure. Various sensors measure the temperatures T and humidity Φ_{soil} at different points in the roof structure as well as the heat flow Φ_q directly into the simulated room under the roof structure. In addition, the amount of water flowing off that cannot be completely absorbed by the substrate is measured. The weather data (air temperature and humidity, solar radiation, atmospheric longwave radiation, wind direction and speed, and amount of rain) are recorded at the weather station at CAE. The schematic measurement setup is shown in Figure 4.

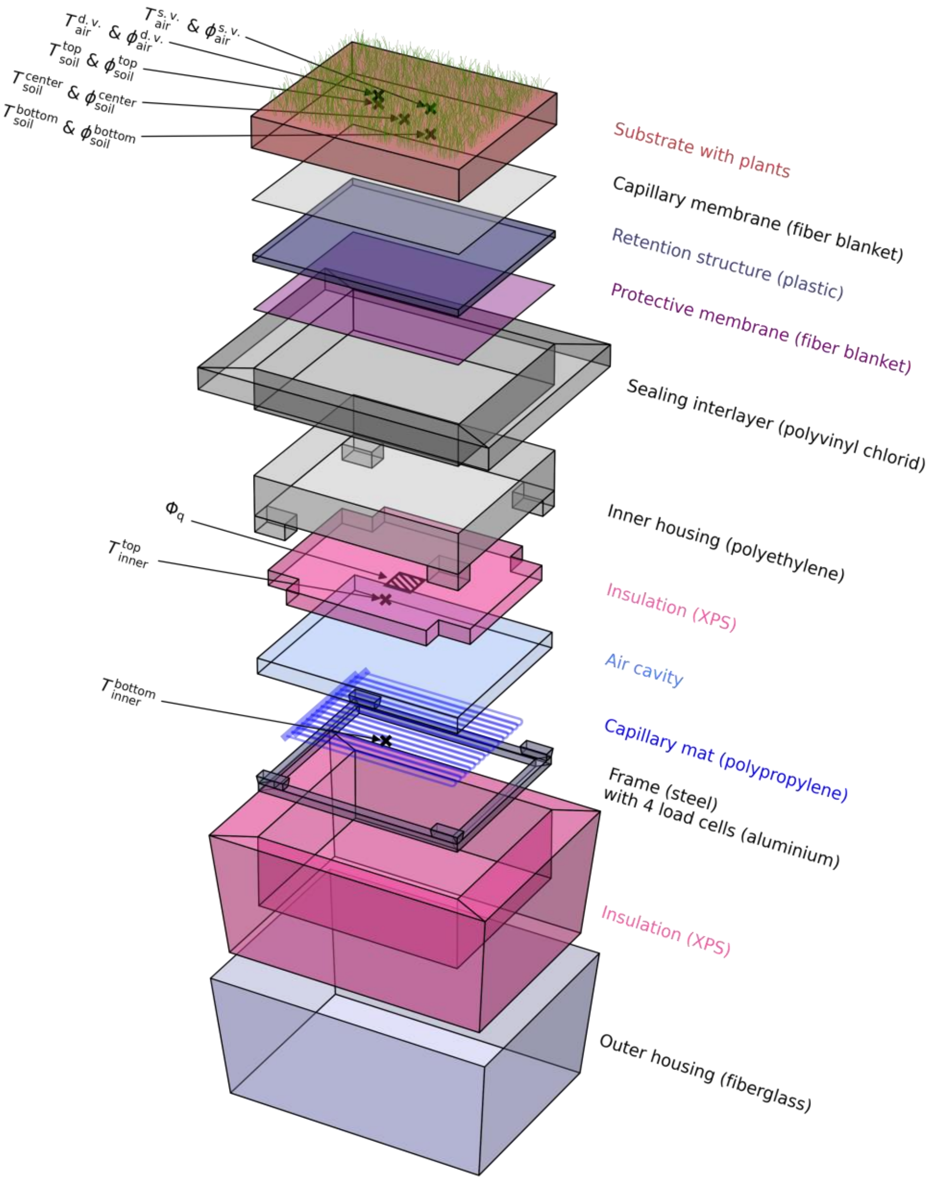

Fig. 4: Exploded view of the outdoor measurement setup for the roof constructions. Various sensors are placed at different points in the roof structure, temperature T, humidity Φ_{soil} and the heat flow Φ_q.

A gravel roof with a fill thickness of 6 cm is chosen as a reference field. Five green roof structures according to Table 1 were also installed. A picture of the roof systems is shown in Figure 5.

Tab. 1*: Planting list of green roof systems for outdoor measurements.*

Name	**System manufacturer**	**Plants**
Extensive 6 cm	6 fürs Grün GmbH, Germany	Sempervivum tectorum Sedum floriferum \`Weihenstephaner Gold\` Sedum hybridum \`Immergrünchen\` Sedum album \`Coral Carpet\`
Extensive 10 cm no retention	Paul Bauder GmbH & Co. KG, Germany	Sedum floriferum \`Weihenstephaner Gold\` Sedum album \`Coral Carpet\` Dianthus carthusianorum Euphorbia cyparissias
Extensive 10 cm plus 4 cm retention	Paul Bauder GmbH & Co. KG, Germany	Sedum floriferum \`Weihenstephaner Gold\` Sedum album \`Coral Carpet\` Dianthus carthusianorum Euphorbia cyparissias
Intensive 20 cm plus 7.5 cm retention	Optigrün international AG, Germany	Summer: Alchemilla mollis Achillea tomentosa Nepeta racemosa \`Senior\` Hemerocallis cultorum \`Stella d´oro\` Winter: Alchemilla mollis Campanula poscharskyana Nepeta racemosa \`Senior\` Hemerocallis cultorum \`Stella d´oro\`
Intensive 25 cm plus 4 cm retention	ZinCo GmbH, Germany	Summer: Solanum lycopersicum Cucumis sativum Hemerocallis cultorum \`Stella d\`oro\` Winter: Alchemilla mollis Campanula poscharskyana Nepeta racemosa \`Senior\` Hemerocallis cultorum \`Stella d\`oro\`

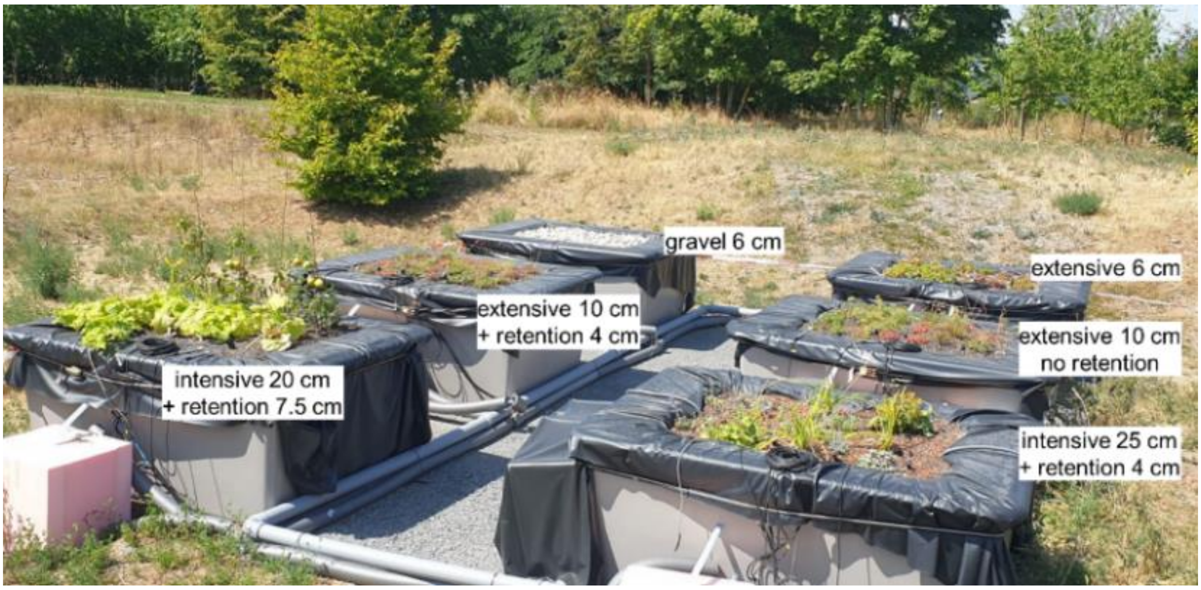

Fig. 5: External measurement setup for five different green roof structures and a reference field (6 cm gravel) on July 19, 2023.

The area under each roof construction is kept at constant temperature by a thermostat via capillary tube mats. The results for the heat flow into the simulated room below the system are presented for both a summer and a winter period. Additionally, water inflow and outflow as well as the amount of rain and the amount of evapotranspiration from the superstructure were recorded.

3.2 Summer measurements of green roof systems

The planting was carried out on June 21, 2023 by the project partner Bavarian State Institute for Viticulture and Horticulture (LWG) located in Veitshöchheim (Germany) and was individually adapted for the different structures. The substrate also differed for the individual structures, as each manufacturer used his own substrate (see Table 1). Only the two extensive setups with a substrate thickness of 10 cm use identical substrates. The superstructures exhibit systematic differences, but thus reflect the behavior of the manufacturers' original systems. Four of the green roof systems are not watered automatically, but are watered manually if necessary, e.g. during long periods of drought. Only for the system “Intensive 25 cm with 4 cm retention” a drip hose was inserted into the substrate and the automatic watering system prepared. However, the automatic watering system was off during the measurement period described here.

The green roof structures are insulated at the bottom with a 10 cm thick layer of extruded polystyrene (XPS), which corresponds to a U-value of 0.35 $W \cdot m^{-2} \cdot K^{-1}$. The superstructures therefore correspond to a moderately to well insulated roof structure.

The measurements were evaluated for the summer period from 2023/08/17 - 2023/09/24, with the “room” temperature set to 24 °C. During this period, there were two dry hot spells with daily maximum temperatures sometimes well above 30 °C (2023/08/17 – 2023/08/24 and 2023/09/4 – 2023/09/17) and two cooler periods with some precipitation (2023/08/25 – 202309/03 and 2023/09/18 – 2023/09/24).

The heat flows on the bottom of the roof towards the "room" were measured using a heat flux plate, as these directly reflect the heat inputs and losses through the roof structure. In addition, the evapotranspiration performance of the systems was recorded by weighting. The data from the load cells was averaged hourly and the difference from midnight to midnight was then determined for each day. Days with rain were usually not taken into account, as unreasonable values often resulted despite recording the rain and runoff volume. Furthermore, the soil moisture was analyzed and correlated with the evapotranspiration quantities and heat inputs. For this purpose, three soil moisture sensors were installed at a depth of 5 cm and their values were averaged. The results are shown in the following figures.

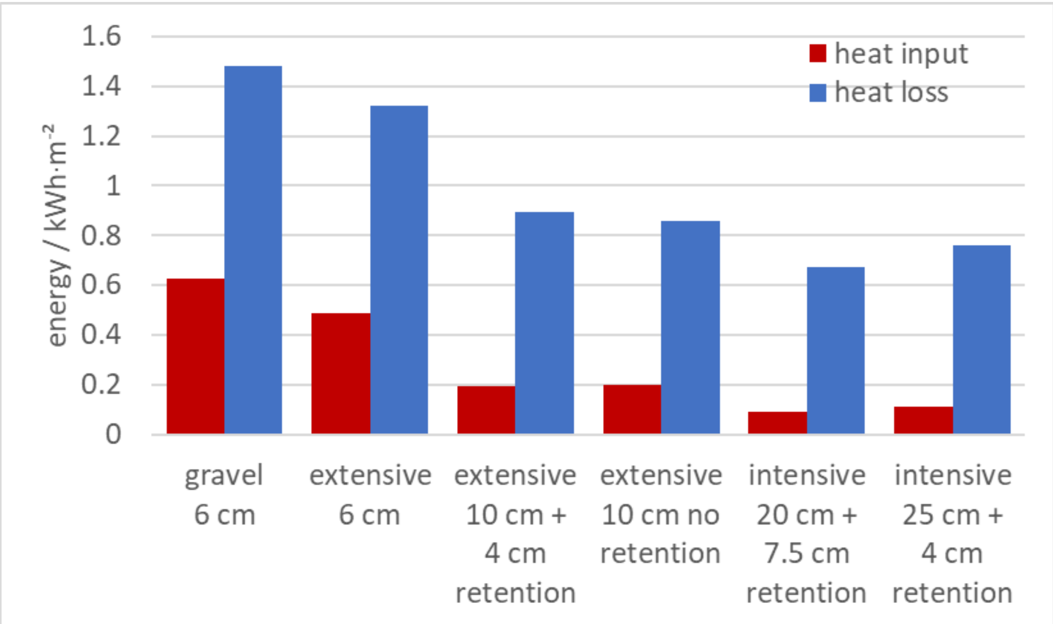

Fig. 6: Total heat inputs and losses of the green roof systems for the measurement period from August 17 to September 24, 2023.

The total heat input can be drastically reduced in some cases by the green roof systems (see Figure 6). The thicker the substrate layer of the structure, the greater the reduction. A retention layer also has a positive effect, but this effect appears to be only slightly pronounced.

In addition to heat input, green roof systems also reduce heat losses, which makes it more difficult for the roof structure to cool down the room below, e.g. on clear summer nights. Overall, the heat losses predominate during the measurement period, so that the net balance of the green roof systems is worse than that of the reference roof. Green roof systems thus reduce cooling load peaks, but can possibly lead to a higher base load if there is no option for night ventilation. However, the exact impact of this effect on the room below and its cooling balance can only be determined using a more precise dynamic analysis (thermal building simulation).

Figure 7 shows the relative daily heat input of the six roof structures for a hot and dry week without any rain in August 2023. The data for the reference roof are set to 100 %. When the substrate dries out during the first five days, the heat input reduction potential of the green roofs is strongly reduced. This occurs especially at the thinner green roof constructions with the 6 cm extensive green roof having even higher heat inputs than the reference roof from August 19. The soil moisture of this green roof construction drops to values close to 0 % (not shown in the graph), meaning that the substrate dries out almost completely. After the soil moisture is raised again by manual irrigation on August 22, the heat inputs then drop again to values that are significantly below those of the reference roof. A sufficient cooling effect of green roof systems can therefore only be achieved with sufficient soil moisture.

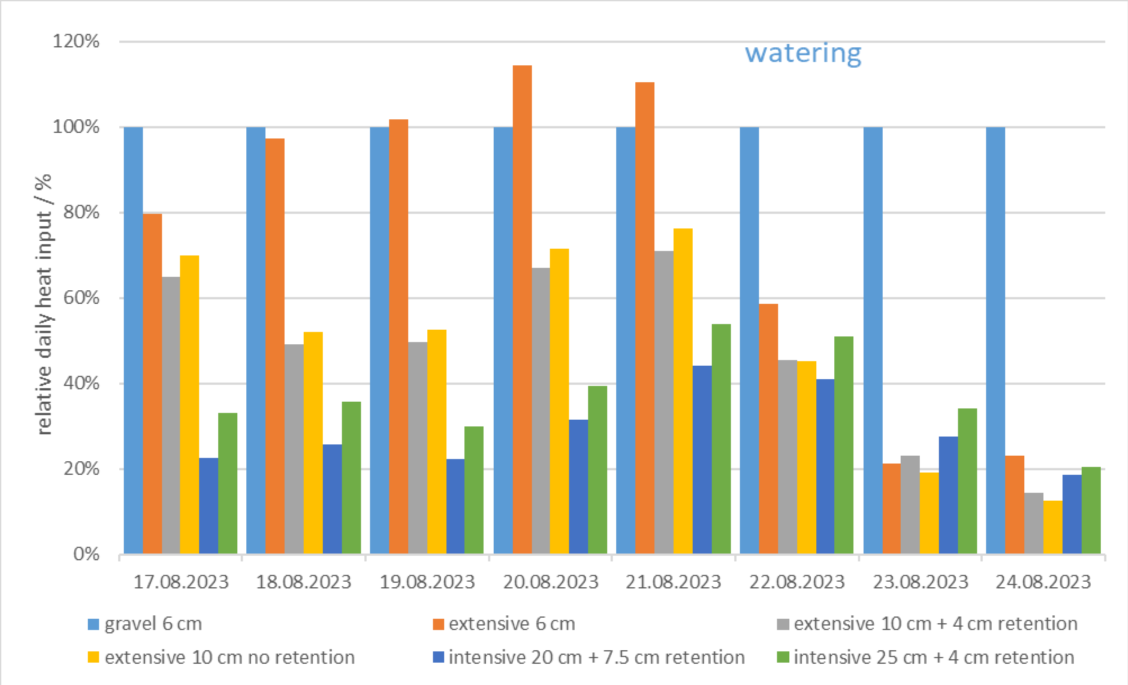

Fig. 7: Daily heat input relative to the reference field with 6 cm gravel for five different green roof structures.

The average soil moisture at 5 cm depth of the different green roof structures for the entire measurement period is shown in Figure 8. The structure with a substrate thickness of only 6 cm shows the lowest average soil moisture and the greatest fluctuations. A retention volume favors a higher average soil moisture and a higher minimum soil moisture (cf. the two structures with 10 cm substrate thickness). A thicker substrate layer also has a positive effect on maintaining soil moisture during dry periods, although this effect only becomes visible after longer periods. While the roof structure with a substrate thickness of 6 cm dries out completely during this period and the structures with a substrate thickness of 10 cm fall to values below 40 %, the average soil moisture in the thicker intensive structures remains at values of 60 - 70 %. The higher soil moisture levels are always found in the two intensive structures with 20 cm substrate thickness and 7.5 cm retention layer. The thickness of the retention layer therefore appears to have a greater influence than the substrate thickness.

The mean daily evapotranspiration of the roof constructions is shown in Figure 9.

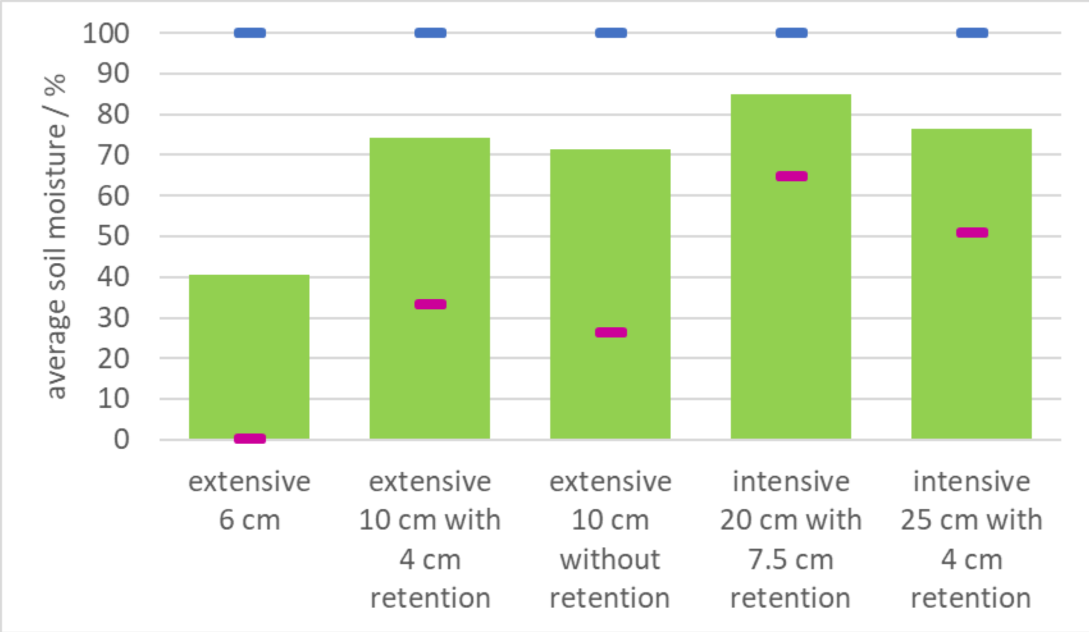

Figure 8: Measured mean values of soil moisture with minimum (pink bars) and maximum (blue bars) values at a soil depth of 5 cm for the green roof systems for the measurement period from August 17 to September 24, 2023.

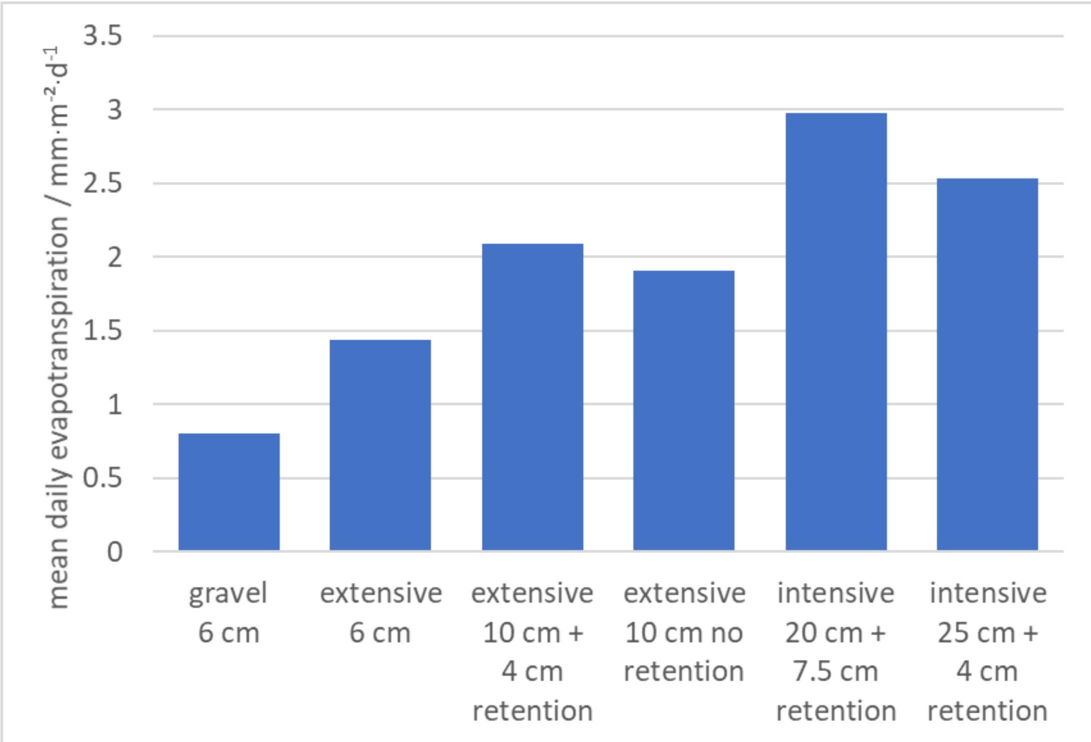

Figure 9: Measured mean daily evapotranspiration of the green roof systems for the measurement period from August 17 to September 24, 2023.

There is a clear correlation between the amount of evapotranspiration, which significantly determines the cooling effect of the roof structures and is directly associated with the reduction in heat input (see Figure 7), and the substrate thickness. The superstructure with a substrate thickness of 6 cm evapotranspirates approx. 1.5 $mm \cdot m^{-2} \cdot d^{-1}$, the superstructures with 10 cm around 2 $mm \cdot m^{-2} \cdot d^{-1}$, and the superstructures with 20 cm or 25 cm 2.5 – 3 $mm \cdot m^{-2} \cdot d^{-1}$. The positive influence of the retention layer is also clearly recognizable. It is interesting to note that a certain amount of evaporation can also be observed on the reference roof with 6 cm of gravel.

Thermography was used to determine how the different structures affect the surface temperatures and therefore the microclimate in the surrounding area. Although the surface temperature is also measured using temperature sensors, these were often exposed to the sun during the measurement period due to the still relatively low growth density of the vegetation. The thermographic images are shown in Figure 10.

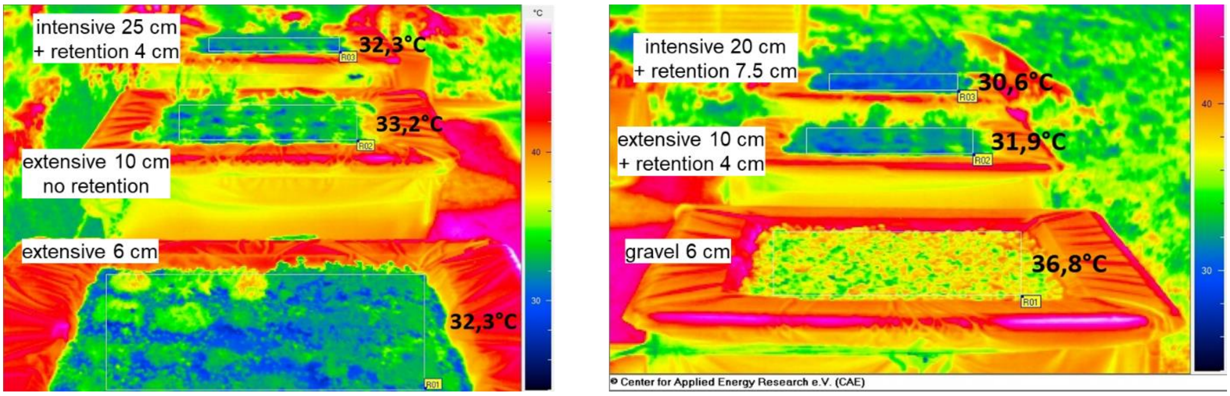

Fig. 10: Thermographic images of the six roof structures shortly after installation.

Although the plant growth directly after planting is still low, the green roof structures show a reduction in surface temperatures of 3 – 6 °C compared to the reference roof with gravel.

3.3 Winter measurements of green roof systems

Before the start of the measurements in winter, the plants in the two intensive green roof structures were partially replaced by the LWG so both fields now have identical plants, but still have different substrates.

The winter measurements were analyzed for the period from October 15, 2023 to April 04, 2024, with the thermostat temperature set to 21 °C. This period was characterized by strong temperature fluctuations and included periods with very cold, but also relatively warm days for winter conditions. Until the beginning of January, the weather was very humid with almost daily precipitation. It was not until January 5, 2024 that a dry period began with average daily temperatures dropping below freezing for several days.

Heat inputs did not play a role or were not present in the period shown. The evapotranspiration performance of the systems was not analysed over the winter, as the measured data often did not show meaningful values due to the persistent rain. The soil moisture was analysed, whereby some of the soil moisture sensors were repositioned before the start of the winter measurements. In the extensive roof structures with 6 cm and 10 cm, all three soil moisture sensors remained at a depth of 5 cm; in the roof structure with 20 cm, one sensor was relocated to a depth of 10 cm; in the roof structure with 25 cm, one sensor was relocated to a depth of 10 cm and another to a depth of 15 cm. In the two thicker intensive structures, it was thus possible to record a moisture profile over the soil depth (not part of this paper). The results are shown in the following figures. The relative heat losses in percent related to the reference roof are shown in Figure 11.

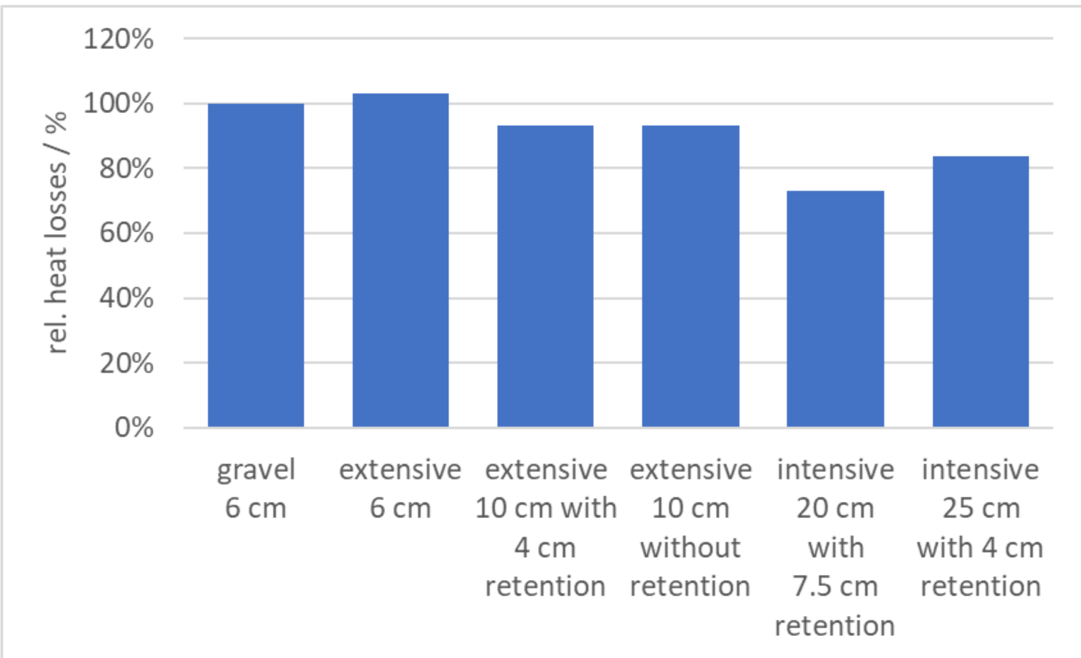

Figure 11: Measured relative heat losses of the green roof systems related to the heat input of the reference roof (set to 100 %) for the measurement period from 2023/10/15 – 2024/04/04.

Due to slightly different internal temperatures of the measurement boxes, the heat flows for the evaluation of the winter measurements were corrected using the average temperature differences between the measurement boxes and the outside air. The results show that certain heat loss reductions can be achieved with the thicker green roof structures. These are 7 % for the two structures with 10 cm substrate thickness, 27 % for the structure with 20 cm substrate thickness and 7.5 cm retention, and 16 % for the structure with 25 cm substrate thickness and 4 cm retention. The structure with a substrate thickness of 6 cm shows a slight increase in heat losses of 3 % compared to the reference roof. With an appropriate structure, green roofs can therefore contribute to a significant reduction in heating demand in winter. In residential buildings, the proportion of heat loss via the roof is generally between 15 % and 30 %. With an optimised green roof, savings in heating consumption by installing a green roof of approx. 3 – 7 % should therefore be achievable.

The soil moisture data show relatively high mean values, as was to be expected due to the persistent precipitation during the measurement period. However, the minimum values, some of which are surprisingly low, are striking. This is due to the start and mid times of the measurement period. At the beginning of the measurements, the ground was still dry from the summer, while in the mid of the measurement period the roof structures were probably partially affected by ground frost, so that the moisture sensors no longer showed a signal. Some moisture sensors showed strange signals even after the frost period, therefore the soil moisture was only evaluated from October 20, 2023 to January 7, 2024 (see Figure 12). The data show the expected high mean values of around 80 % for the structure with a substrate thickness of 6 cm and more than 90 % for all other systems. The minimum values reflect the water storage capacity of the superstructures and are 16 % for the thin superstructure, 54 % and 62 % for the other two extensive superstructures and 62 % and 68 % for the thicker intensive superstructures.

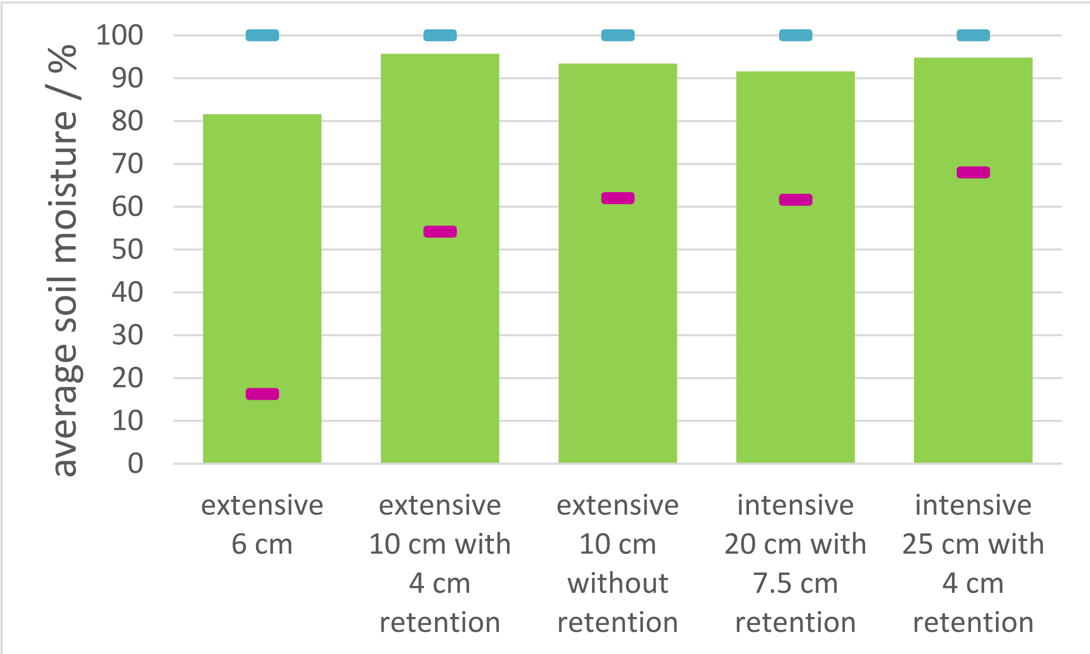

Figure 12: Measured mean values of soil moisture with minimum (red bars) and maximum (blue bars) values at a soil depth of 5 cm for the green roof systems for the shortened measurement period from October 20, 2023 to January 7, 2024.

4. Conclusions

Measurements taken outdoors in the summer months in the temperate Central European climate zone (Würzburg, Germany) show that green roofs have a cooling effect if the substrate moisture is sufficient. Green roof structures with a higher substrate thickness with additional retention exhibit lower fluctuations in moisture content and therefore also in the cooling effect. Retention volumes in green roof structures are not only suitable for storing rainwater and intercepting heavy rainfall events, but are also able to bridge long periods of drought and increase the evapotranspiration capacity of the overall system. By reducing the maximum surface temperatures, green roofs have a positive effect on the microclimate in city centers. On the building level, a green roof means reduced heat input and therefore lower cooling load peaks during the day, but the green roof also reduces night-time cooling via the roof.

During the winter period, green roof structures with a substrate thickness of 10 cm or more reduce heat losses through the roof. We measured maximum reductions in heat losses of 27 % for an intensive green roof with 20 cm substrate plus 7.5 cm retention. Thinner green roof constructions show no energy savings potential or can even increase the heat losses slightly, as was measured for an extensive green roof with 6 cm substrate and an increase in heat losses of 3 % compared to a reference roof with 6 cm gravel.

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- Optigrün international AG, Am Birkenstock 15-19, 72505 Krauchenwies-Göggingen, Germany, Handelsregister: HRB 711009
- ZinCo GmbH, Lise-Meitner-Straße 2, 72622 Nürtingen, Germany, Handelsregister: HRB 789793

References

Besir, A.B., Cuce, E., 2018. Green roofs and facades: A comprehensive review. Renewable and Sustainable Energy Reviews 82, 915-939.

Bevilacqua, P., 2021. The effectiveness of green roofs in reducing building energy consumptions across different climates. A summary of literature results. Renewable and Sustainable Energy Reviews 151, 111523.

Bevilacqua, P., Bruno, R., Arcuri, N., 2020. Green roofs in a Mediterranean climate: energy performances based on in-situ experimental data. Renewable Energy 152, 1414-1430.

Guattari, C., Evangelisti, L., Asdrubali, F., De Lieto Vollaro, R., 2020. Experimental Evaluation and Numerical Simulation of the Thermal Performance of a Green Roof. Applied Sciences 10(5), 1767.

Ketut Acwin Dwijendra, N., Muda, I., Milanes, C.B., Bharath Kumar, N., Abosinnee, A.S., Akhmadeev, R., 2023. How do green roofs affect per capita energy consumption in residential buildings under various climate conditions? Sustainable Energy Technologies and Assessments 56, 103127.

Koroxenidis, E., Theodosiou, T., 2021. Comparative environmental and economic evaluation of green roofs under Mediterranean climate conditions – Extensive green roofs a potentially preferable solution. Journal of Cleaner Production 311, 127563.

Richter, M., Dickhaut, W., 2023. Long-Term Performance of Blue-Green Roof Systems—Results of a Building-Scale Monitoring Study in Hamburg, Germany. Water 15(15), 2806.

Salvalai, G., Marrone, G., Maria Sesana, M., Imperadori, M., 2023. Lightweight extensive green roof for building renovation: Summer performance analysis and application in a living laboratory. Energy and Buildings 298, 113589.

Schade, J., Lidelöw, S., Lönnqvist, J., 2021. The thermal performance of a green roof on a highly insulated building in a sub-arctic climate. Energy and Buildings 241, 110961.

Yang, Y., Davidson, C.I., Zhang, J., 2021. Evaluation of thermal performance of green roofs via field measurements and hygrothermal simulations. Energy and Buildings 237, 110800.

Yıldırım, S., Özburak, Ç., Özden, Ö., 2023. Green Roofs, Vegetation Types, Impact on the Thermal Effectiveness: An Experimental Study in Cyprus. Sustainability 15(3), 2807.