Thermal Characterization of Living Wall Systems

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Abstract

The energetic impact of several Living Wall Systems (LWS) was measured in the laboratory and in an outdoor test facility in Würzburg, Germany. It was found, that the usual rear ventilation of the systems reduces their thermal benefits in winter. When estimating the energy savings potential of LWS, the solar absorptance of the façade has to be taken into account. When installed on facades with medium to high solar absorptance values, LWS can even increase the heat losses in winter. In summer, the cooling potential of LWS is higher on facades with high solar absorptance values while it is strongly reduced on façades with low solar absorptance. However, when considering solar absorptance on walls to regulate heat losses in winter and heat gains in summer, this needs opposite measures, while LWS show their advantages equally in both seasons.

Keywords: façade greening, Living Wall System, thermal performance, energy savings, U-value

1. Introduction

Façade greening has a number of positive effects such as improving the air quality, decreasing the heat island effect, enhancing biodiversity, decreasing the noise level, and improving thermal behavior of buildings (Ogut et al. 2022). While the first points are good for the environment, the last point in particular is important for building operators and users, as any savings in cooling or heating energy pay off directly for them. While façade greening incorporates different kinds of systems, like Green Walls where the plants are planted in the ground, according to Mann et al. (2023), an increasing market for façade greening is Living Wall Systems (LWS) that use modular structures with substrate layers in a curtain wall construction.

While the effects of LWS regarding their temperature reduction potential have been widely studied, much less publications investigate their energetic effects. Susca et al. (2022) reviewed the number of articles dealing with specific topics: they found 5 articles dealing with heating energy, 13 articles for cooling energy, and 30 articles investigating surface temperature effects. Since several of the articles use simulations only, the numbers show a need for experimental work in this field. The following passages discuss some of the relevant results already published.

Bianco et al. (2017) investigated a newly developed LWS in a test cell in Turin, Italy, with a south facing wall with a U-value of 0.4 W m^{-2} K^{-1}. They found a reduction in heat losses during winter conditions of 56 % to 58 % for the LWS compared to the reference wall. During summer conditions, the LWS performed worse than the reference wall. According to the authors, the heat fluxes during summer were very small and in the range of error of the heat flux meter. The paper does not mention the solar absorptance of the reference wall, however, according to the pictures, the reference wall looks bright white.

The same LWS was measured in a real-scale demonstration mock-up (Serra et al. 2017). The reference wall had an additional insulation layer of 3 cm extruded polystyrene foam (XPS) to give both constructions an effective U-value of 0.3 W m^{-2} K^{-1}. An equivalent thermal transmittance of 0.29 W m^{-2} K^{-1} was measured for the wall with LWS while 0.25 W m^{-2} K^{-1} was measured for the reference wall.

Djedjig et al. (2017) investigated the thermal performance of a west façade with LWS in La Rochelle, France. The setup used empty concrete tanks as scaled-down buildings. A block without LWS with a façade solar reflectance of 0.64 was used as reference. The 5 cm concrete walls had no insulation. The LWS reduced heat

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gains by 97 % and heat losses by about 30 % in summer. In winter, heat gains were reduced by 40 % whereas heat losses were reduced by about 80 %. This study differs from the others listed here in that the indoor temperatures in winter were free floating.

Tudiwer and Korjenic (2017) measured two different LWS at two buildings in Vienna, Austria, during winter. They compared the measured heat fluxes of the greened façade with a non-greened part of the façade as reference. The two wall constructions without LWS had U-values of 0.75 to 0.79 W m^{-2} K^{-1} and 0.35 to 0.37 W m^{-2} K^{-1}, respectively. With LWS, the authors found an overall reduction in U-value of 20 % to 22 % for the first wall construction and of 17 % to 22 % for the second.

Fox et al. (2022) measured the energetic effect of a LWS on a non-insulated building during winter in Plymouth, UK. They found an improvement in insulation by the LWS of 31.4 % compared to the reference wall with a U-value of 1.12 W m^{-2} K^{-1}.

All these publications provide indications of the positive effect of LWS for improving the energy efficiency of buildings, which could lead to the following assumptions:

- LWS generally reduce heat gains of walls in summer (Bianco et al. 2017 got different results, however, they attributed this to the measurement uncertainty due to the small heat flows),
- LWS generally reduce heat losses of walls in winter,
- the higher the U-value of the wall, the greater the effect of the LWS.

While the last conclusion is in accordance to building physics, the first two conclusions seem to miss one important aspect of the energy balance of walls: the shading effect of the LWS. Since LWS cover the wall completely due to the opaque back layer – even if the plants shed their leaves in winter – the solar absorptance of the wall should play an important role in the energy balance. In this sense, the LWS must be understood not only as a thermal insulation system but also as a solar shading system even in winter. None of the above listed articles, apart from Djedjig et al. (2017), however, do mention the solar absorptance or at least the brightness of the reference wall.

In order to clarify this, the thermal performance of façade greening is being systematically investigated and quantified in the project U-green. This includes laboratory measurements in a Hot-Box system to determine the stationary U-value, as well as dynamic outdoor measurements on test façades. The long-term goal of the project is to determine calculation methods for the energy assessment of façade greening in standards and building energy laws.

2. Laboratory Measurements

Several Living Wall Systems (LWS) were measured in a computer-controlled Hot-Box system (see Figure 1) in accordance with ASTM C236-89 (1989) to determine their heat transmission coefficient in steady state. In the Hot-Box system a sample is installed between two compartments with different temperatures and the heat flow density is determined via the energy supply in the heated compartment needed to maintain the steady state. The thermal coefficients are calculated with the environmental conditions selected using the heat flow density and the temperature difference.

The LWS were mounted onto a reference wall construction that was measured separately. The LWS sample size ranged from 0.9 m^{-2} for the gabion system and modular system 2 up to 1.7 m^{-2} for the tray system and modular system 1. The results were corrected for the different sample sizes. By comparing the U-values of the reference wall with LWS U_{LWS} with the U-value of the reference wall without LWS U_{ref}, the thermal resistance of the LWS R_{LWS} was calculated according to eq. 1:

$$R_{LWS} = \frac{1}{U_{LWS}} - \frac{1}{U_{ref}} \qquad \text{(eq. 1)}$$

Living Wall Systems usually have an air gap for rear ventilation. The measurements in the Hot-Box were therefore also carried out with an air gap. The wind speed in the cold chamber was 1.6 m s^{-1} for the reference wall, while some LWS reduced the wind speed to values as low as 0.3 m s^{-1}. Additional measurements with a closed air gap show the influence of this rear ventilation on the thermal performance. The results are shown in Table 1.

Fig. 1: Hot-Box system (top left), reference wall (top mid), and LWS samples: gabion system (top right), tray system (bottom left), modular system 1 (bottom mid), and modular system 2 (bottom right).

Tab. 1: U-values of different kinds of LWS measured in a Hot-Box system.

System	U-value [W m^{-2} K^{-1}]	ΔU [%]	R_{LWS} [m^2 K W^{-1}]
Reference wall	0.83 ± 0.02	0	-
LWS (gabion system) rear ventilated	0.75 ± 0.02	10	0.13 ± 0.02
LWS (tray system) rear ventilated	0.74 ± 0.02	11	0.15 ± 0.02
LWS (modular system 1) rear ventilated	0.74 ± 0.02	11	0.15 ± 0.02
LWS (modular system 2) rear ventilated	0.72 ± 0.02	13	0.18 ± 0.02
LWS (gabion system) air gap closed	0.58 ± 0.02	30	0.52 ± 0.02
LWS (tray system) air gap closed	0.68 ± 0.02	18	0.27 ± 0.02
LWS (modular system 1) air gap closed	0.69 ± 0.02	17	0.24 ± 0.02
LWS (modular system 2) air gap closed	0.64 ± 0.02	23	0.36 ± 0.02

With rear ventilation, the measured R-values of the Living Wall Systems are equivalent to 4 to 7 mm expanded polystyrene foam (EPS) insulation, ranging from 0.13 to 0.18 m² K W^{-1}, and almost identical, regardless of the system structure. With suppressed rear ventilation, the values are much higher – 0.24 to 0.52 m² K W^{-1} or equivalent to 8 to 18 mm EPS – and there are bigger differences between the systems. Some manufacturers use very thick substrate layers, e.g. gabion system, or thin insulation layers in their systems, e.g. modular system 2. However, their thermal advantages can only be utilized if the LWS will be installed without rear ventilation.

These values provide an initial indication that LWS can have a certain energy savings effect on poorly insulated walls, but their thermal impact on better insulated walls or new buildings is limited.

3. Outdoor Measurements

Since the Hot-Box measurements in the laboratory exclude important solar thermal effects of LWS like shading, we used an outdoor test facility for additional measurements. The test facility is a container with a floor area of 6 m x 3 m and a height of 3 m. The 10 cm concrete walls are insulated with 18 cm mineral wool, which gives a U-value of 0.2 W m^{-2} K^{-1}. The inside is temperature-controlled by an air conditioning unit. We used the south and west façade to investigate the thermal effect of different kinds of LWS. A sketch of the setup is depicted in Figure 2. The two façades were divided into separate wall sections, four on the south and six on the west façade (see Figure 2 right). Each wall section can accommodate a LWS or serve as a reference field without greening. Due to some problems with the setup on the west façade, we focus in this paper on the results for the south façade only.

Fig. 2: Sketch of the measurement setup for LWS on our outdoor test facility (left) and southwest view of the test facility with frames for the LWS and designations for the wall sections (right).

As can be seen in Figure 2 right, sections S3 and S4 have a brighter plaster than the other sections. A solar reflectance measurement of the two plaster samples yielded a solar absorptance α_S of 0.6 for the medium and 0.24 for the bright plaster. The medium plaster therefore is a good reference, because a solar absorptance of 0.6 is a typical value for building façades according to the German standard DIN V 18599-2 (2018), which gives a range of 0.4 to 0.8 for bright and dark façade surfaces, respectively, and it uses a standard value of 0.6 if more precise values are not known.

The energetic impact of the LWS was measured via heat flux sensors positioned on the inside wall surface of every wall section. The heat flux therefore directly gives the heat gains and losses of the room through the respective wall section.

3.1 Summer Measurements

In a first measurement period from July 11 to September 5, 2023 we investigated the summer performance of two LWS on the south façade (S3, S4) while the two wall sections S1 and S2 had no LWS and were used as reference wall. The room temperature was set to 24°C. Pictures of the façade at the beginning and after the measurement period are shown in Figure 3 and a list of the installed LWS is given in Table 2. All LWS use the same substrate (DG EXT Dachgartensub.extensiv, Patzer Erden, Germany) and the same plant mix (see Table 3). An automatic irrigation system with individual parameters for each wall section ensures a consistently high level of humidity in all systems. The LWS are mounted on holders and stand in front of the façade without any direct contact. The distance between LWS and facade is about 5 cm and the sides are all open to wind and rain.

Fig. 3: South façade with two different LWS at the beginning of the measurement period on July 20, 2023 (left) and after the measurement period on September 20, 2023 (right). In the right picture, there's already a new system installed on S2 for the winter measurements; this was not measured during summer.

Tab. 2: Description of the LWS used in the summer measurements.

Wall Section	System	Company	Façade area
S1, S2	Reference without LWS	-	1.84 m² / 2.57 m²
S3	greencityWALL	floor-design Wand GmbH, Germany	2.57 m²
S4	Tray system	Tech Metall Erzeugungs Handel und Montage GmbH, Austria	1.84 m²

Tab. 3: Plant mix used in the LWS.

Description	Botanical Name
Mix sunny	Stachys monnieri \`Hummelo\` Campanula poscharskyana Heuchera villosa var. macrorrhiza Bergenia cordifolia \`Rosi Klose\` Fragaria vesca semperflorens \`Alexandria\` Thymus praecox \`Minor\` Potentilla thurberi \`Monarch\`s Velvet\` Origanum vulgare \`Compactum\`

The heat flux sensors are HFP01 from the company Hukseflux, Netherlands, with a relative uncertainty of ± 3 %. The measurement data are recorded by Agilent data loggers at one-minute intervals and stored in a SQL database. The weather data is recorded at a weather station about 50 meters away and also exported into the SQL database. All raw data is then exported with the Monisoft[1] evaluation software in precisely timed 5-minute steps for further analysis in Excel.

Figure 4 left shows the weather data and Figure 4 right depicts the summarized heat gains and losses through

[1] https://fbta.ieb.kit.edu/monisoft.php

the wall sections for the summer measurement period. The weather was mixed with several cold periods with maximum daily temperatures below 20°C but also with some hot periods with maximum daily temperatures of more than 30°C.

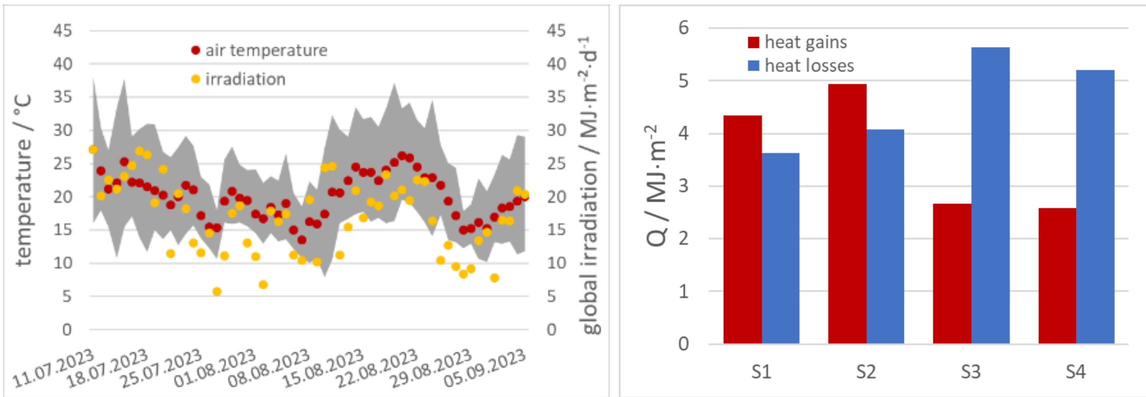

Fig. 4: Measured daily mean air temperature (red dots), minimum and maximum daily air temperature (grey area), and horizontal solar global irradiation (left); summarized heat gains and losses through the wall sections S1 and S2 without and S3 and S4 with LWS (right).

The measured data show some slight differences between the two reference walls S1 and S2 with S2 having 14 % higher heat gains and 12 % higher heat losses than S1. For the reference walls, the heat gains are higher than the heat losses. The walls with LWS have significantly lower heat gains than the reference walls, the reduction is 38 % to 40 % if compared to S1 and 46 % to 48 % if compared to S2. The heat losses of the walls with LWS on the other hand are much higher than that of the reference walls. This indicates, that LWS on the south façade reduce heat gains through walls with a solar absorptance of 0.6 while they do not prevent the room from cooling down through the wall. On the south façade, such walls without LWS show a negative energy balance with regard to heat input (more gains than losses), while the balance is clearly shifted into positive region (more losses than gains) with a LWS.

3.2 Influence of solar absorptance in summer

To estimate the influence the solar absorptance of the wall has on this effect, we determined the heat gains and losses of the walls with LWS compared to a reference wall with bright plaster with a solar absorptance α_S of 0.24. To do this, we measured all four wall sections without LWS. This was done between May 23 and June 11, 2023, before the LWS were installed. Since we wanted to focus on the effect α_S has on the heat gains, we set the room temperature to 21°C. Figure 5 shows the weather data as well as the heat gains and losses. The heat losses are just for information and are not used further.

The data show a clear reduction in heat gains for the wall sections S3 and S4 with lower α_S. The heat gains seem to be systematically lower in the top sections S1 and S3 while the heat losses are higher, which indicates temperature stratification in the room.

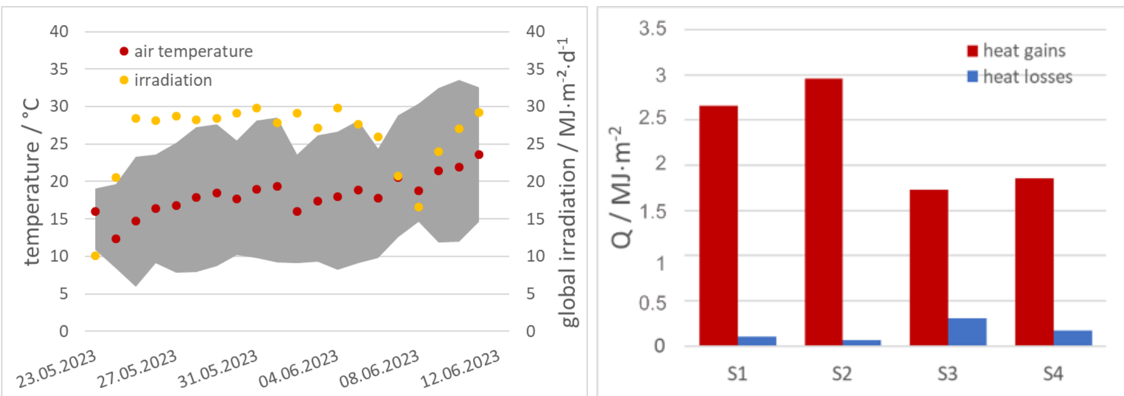

Fig. 5: Measured daily mean air temperature (red dots), minimum and maximum daily air temperature (grey area), and horizontal solar global irradiation (left); summarized heat gains and losses through the wall sections without LWS (right).

With these data we determined the heat gains for the wall sections S1 and S2 with hypothetical bright plaster according to equations 2 and 3:

$$Q_{S1,bright} = \frac{Q_{S3}}{Q_{S1}} \cdot Q_{S1,medium} \qquad \text{(eq. 2)}$$

$$Q_{S2,bright} = \frac{Q_{S4}}{Q_{S2}} \cdot Q_{S2,medium} \qquad \text{(eq. 3)}$$

Q_{Si} are the heat gains from the measurements of S1 to S4 in this section (red bars in Figure 5 right), $Q_{Si,medium}$ are the heat gains of S1 and S2 from the measurements in section 3.1, and $Q_{Si,bright}$ are the hypothetical heat gains of S1 and S2 for the summer measurements in section 3.1 if the wall sections had a bright plaster. This estimate can be made under the assumption that the weather boundary conditions during both measurement periods are similar. The mean outside air temperature for the measurement period in section 3.1 is 20.1°C while that for section 3.2 is 18.1°C. However, the room air temperature in section 3.1 is 24°C while that in section 3.2 is 21°C, which should equalize the differences somewhat. The mean daily solar irradiance on the south façade for section 3.1 is 8.922 ± 0,446 MJ m^{-2} d^{-1} while that for section 3.2 is 11.748 ± 0,587 MJ m^{-2} d^{-1}. These values show that there are some differences especially regarding the solar irradiation, which is higher in section 3.2. This could lead to relatively more heat gains for the wall sections with medium plaster compared to those with bright plaster in section 3.2, which in turn would underestimate the heat gains $Q_{Si,bright}$. Nevertheless, this estimation should give a feeling for the effects of the solar absorptance.

Table 4 gives an overview of the data used and the results. Figure 6 shows a comparison of the heat gains.

Tab. 4: Measured heat gains for the wall sections S1 and S2 with medium plaster as well as S3 and S4 with bright plaster and estimated heat gains for S1 and S2 with bright plaster. All wall sections are without LWS.

Wall section	Heat gain [MJ m^{-2}]	Description and measurement period
Q_{S1}	2.658 ± 0,080	Medium plaster, section 3.2, measured
Q_{S2}	2.956 ± 0,089	Medium plaster, section 3.2, measured
Q_{S3}	1.728 ± 0,052	Bright plaster, section 3.2, measured
Q_{S4}	1.859 ± 0,056	Bright plaster, section 3.2, measured
$Q_{S1.medium}$	4.335 ± 0,130	Medium plaster, section 3.1, measured
$Q_{S2.medium}$	4.942 ± 0,148	Medium plaster, section 3.1, measured
$Q_{S1.bright}$	2.818 ± 0,085	Bright plaster, section 3.1, estimated
$Q_{S2.bright}$	3.107 ± 0,093	Bright plaster, section 3.1, estimated

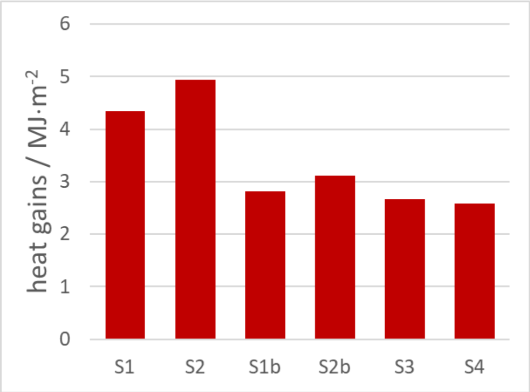

Fig. 6: Comparison of the summarized heat gains through the wall sections: S1 and S2 are measured values without LWS and with medium plaster (α_S = 0.6), S1b and S2b are estimated values without LWS and with bright plaster (α_S = 0.24), S3 and S4 are measured values with LWS.

The data in Figure 6 show that the bright plaster in wall sections S1b and S2b reduces the heat gains to almost the same level as the LWS (S3 and S4). While the LWS reduce the heat gains compared to a medium plastered wall with α_S = 0.6 by 38 % to 48 %, they show a much slighter reduction of 5 % to 17 % compared to a bright plastered wall with α_S = 0.24.

3.3 Winter Measurements

In a second measurement period from November 22, 2023, to April 5, 2024, we investigated the winter performance of three LWS on the south façade. Pictures of the façades are shown in Figure 7 and a list of the installed LWS is given in Table 5.

Fig. 7: South façade with three different LWS before the measurement period on September 20 2023 (left) and near the end of the measurement period on February 2 2024 (right).

Tab. 5: Description of the LWS used in the winter measurements.

Wall Section	System	Company	Façade area
S1	Reference without LWS	-	1.84 m²
S2	fytotextile	Verticalgreendesign GmbH, Germany	2.57 m²
S3	greencityWALL	floor-design Wand GmbH, Germany	2.57 m²
S4	Tray system	Tech Metall Erzeugungs Handel und Montage GmbH, Austria	1.84 m²

As in the summer measurements, all LWS use the same substrate and the same plant mix. During winter the LWS were not irrigated. The holders have no direct contact to the façade with a distance of about 5 cm and the sides are all open to wind and rain.

As there were signs of temperature stratification in the room, additional temperature sensors were installed to measure the inside air temperature directly in front of each wall section. With the mean temperature of the inside air $\bar{T}_i$, the mean temperature of the outside air $\bar{T}_o$, the summarized heat losses Q_{loss}, and the duration t of the measuring period, an effective U-value U_{eff} was determined for each wall section according to equation 4:

$$U_{eff} = \frac{Q_{loss}}{(\bar{T}_i - \bar{T}_o) \cdot t} \qquad \text{(eq. 4)}$$

This evaluation via U_{eff} corrects for differences in the internal air temperature T_i between the individual wall sections. The heat gains measured in winter are so small that they are not considered further. Figure 8 left shows the weather data and Figure 8 right depicts the calculated U_{eff} values of the wall sections for the winter measurement period. The weather was mostly moderate with daily mean temperatures between 5 to 10°C and one longer frost period in January. It was rainy with very little sunshine until the beginning of March.

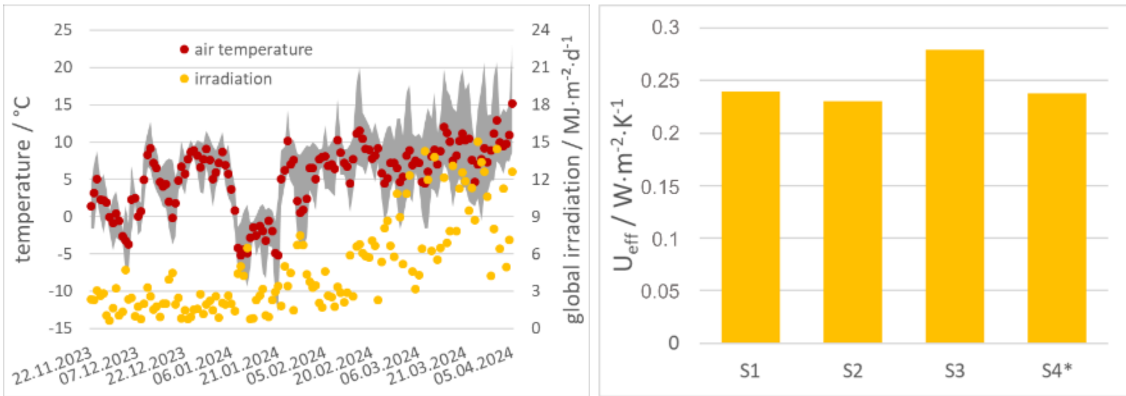

Fig. 8: Measured daily mean air temperature (red dots), minimum and maximum daily air temperature (grey area), and horizontal solar global irradiation (left); U_{eff} values for the wall section S1 without and the wall sections S2 to S4 with LWS (right). *Due to problems with the inside air temperature sensor of S4 only data for the following periods are considered: November 22-29, 2023; December 5-6, 2023; December 9 2023 – February 12 2024; March 12-26, 2024.

On the south façade, the LWS do not improve U_{eff} very much compared to a reference wall with a solar absorptance of 0.6. While LWS S2 and S4 show a slight reduction of 4 % and 1 %, respectively, the U_{eff} of LWS S4 is even 16 % higher compared to the reference wall S1. This is a first indication that LWS can lead to greater heat losses, especially when compared to walls with medium to high solar absorptance. Of course, facades with medium to high solar absorptances instead have disadvantages in summer.

3.4 Influence of solar absorptance in winter

To estimate the influence of the solar absorptance, we estimated the heat losses and U_{eff} of the reference wall S1 for a bright plaster with a solar absorptance α_S of 0.24 as described in section 3.2. A measurement of S1 and S3 without LWS between March 17 and May 3 2023 was used as reference. The room temperature was set to 21°C. Figure 9 shows the weather data as well as the heat gains and losses. The heat gains are just for information and are not used further.

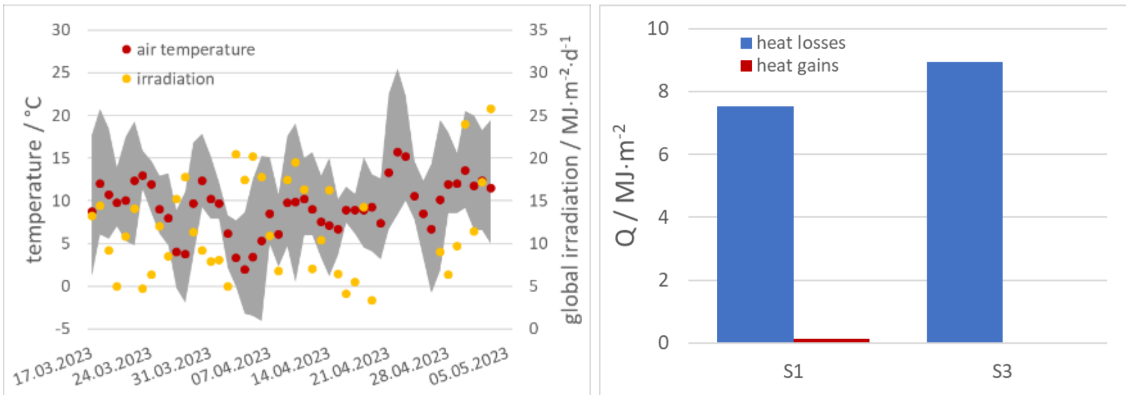

Fig. 9: Measured daily mean air temperature (red dots), minimum and maximum daily air temperature (grey area), and horizontal solar global irradiation (left); summarized heat gains and losses through the wall sections without LWS (right).

$Q_{S1.bright}$ was calculated according to equation 2. Table 6 gives an overview of the data used and the results. Figure 10 shows the U_{eff} values of the south wall sections S2 to S4 of Figure 8 compared to the U_{eff} value for S1 with a bright plaster.

Due to the bright plaster, the U_{eff} value of S1b is about 19 % higher than that of S1. Consequently, the effect of the LWS changes accordingly when compared to S1b instead of S1. While S3 now shows a slight reduction in U_{eff} value of 2 %, the U_{eff} values of S2 and S4 are lower by 19 % and 17 %, respectively.

Tab. 6: Measured heat losses for wall section S1 with medium plaster and S3 with bright plaster and estimated heat losses for S1 with bright plaster. All wall sections are without LWS.

Wall section	Heat loss [MJ m^{-2}]	Description and measurement period
Q_{S1}	7.513 ± 0.225	Medium plaster, section 3.4, measured
Q_{S3}	8.936 ± 0.280	Bright plaster, section 3.4, measured
$Q_{S1.medium}$	46.17 ± 1.39	Medium plaster, section 3.3, measured
$Q_{S1.bright}$	54.91 ± 1.65	Bright plaster, section 3.3, estimated

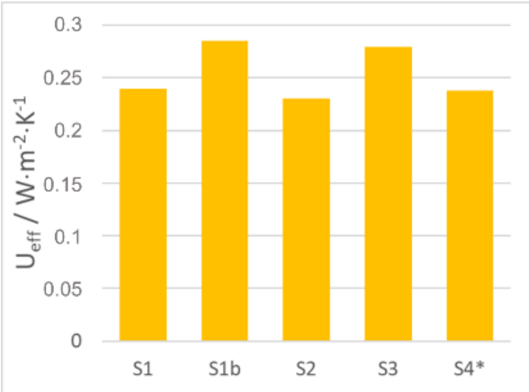

Fig. 10: Comparison of the U_{eff} values of the wall sections: S1 is measured without LWS and with medium plaster (α_S = 0.6), S1b is estimated without LWS and with bright plaster (α_S = 0.24), S2 to S4 are measured values with LWS. *Due to problems with the inside air temperature sensor of S4 only data for the following periods are considered: November 22-29, 2023; December 5-6, 2023; December 9 2023 – February 12 2024; March 12-26, 2024.

4. Conclusions and Outlook

Measurements on different kinds of LWS were performed in the laboratory as well as on a test façade. The laboratory measurements in a Hot-Box system show reduced U-values for all investigated LWS. When rear ventilated, the different kinds of LWS perform almost identical with reductions in U-value of 10 % to 13 %. Without rear ventilation, the U-value reduction is much bigger ranging from 17 % to 30 % and the LWS perform differently, dependent on their design.

The results on the test façade are considerably more varied. With solar radiation effects included, the performance of the LWS on the thermally well-insulated test façade depend strongly on the solar absorptance of the reference wall. Compared to a south wall with a medium plaster with α_S = 0.6, the three investigated LWS show only small reductions of a few percent or in one case even lead to 16 % higher heat losses in winter. Compared to a reference wall with a bright plaster with α_S = 0.24, all three LWS show reductions of 2 % up to 19 %.

In summer, the LWS reduce the heat gains through the wall. The effect of the solar absorptance of the reference wall is reversed here. While a high solar absorptance helps reduce heat losses in winter it generates high heat gains in summer. On the south façade, the two investigated LWS reduced the heat gains by 38 % to 48 % compared to a reference wall with medium plaster but only by 5 % to 17 % for a bright plastered reference.

The positive effects of LWS, lower heat losses in winter and lower heat gains in summer, can also be achieved by adjusting the solar absorption of the wall. However, a high solar absorption value in summer leads to undesirably high heat gains, while a low value in winter increases heat losses. An LWS shows its advantages in both seasons.

The results also show significant differences between the LWS with some performing better than others. Favorable design criteria here appear to be the use of very thick substrate layers, as in the gabion system, and carrier materials with low thermal conductivity, such as foams as in the Fytotextile system.

An important fact to mention is that the LWS are elevated in front of the façade, so that no thermal bridge effects due to retaining structures or screws are included in the measurement data. These thermal bridges have to be taken into account for they can reduce or even overcompensate any savings effects (Tudiwer et al. 2019), especially on well insulated façades.

In a next step, a simulation model shall be validated by the measurements to calculate the energetic effect of LWS on different kinds of buildings.

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