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A nature-based system for improving Mediterranean buildings' performance: contribution to energy saving by heat transfer reduction and influence of climatic parameters

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Key words: Building envelope; green façade; sustainable urban development; passive design; thermal screen; solar shading.

Abstract

Urban environments can be turned greener and more sustainable by letting in vegetation. The application of green façades on buildings' vertical surfaces is a viable option that brings various advantages. This study focuses on the energy benefit provided by an evergreen green façade in Mediterranean climate conditions. The results came from a long experimental campaign, heat fluxes evaluation and statistical analyses. The thermal behaviour of the experimental green façade was analysed all year round, highlighting differences between warm and cold periods and between time of the day. The main advantage was assessed in terms of energy saving, defined as heat flux reduction through the wall covered with vegetation in comparison with an unvegetated wall. The study pointed out that energy saving was achieved throughout the year, but in different time of the day based on the season. A daytime energy saving was obtained in warm periods due to the shading effect and the plants evapotranspiration. A night-time benefit was reached in cold periods mainly thanks to the thermal and wind barrier action of the green layer. The results showed daily mean values of energy saving equal to 11.47 W m^{-2} for a warm period and to 3.23 W m^{-2} for a cold period. The statistical analysis highlighted that the energy saving was positively influenced by external air temperature especially at daytime. Overall, higher energy saving was provided by the green façade when higher external air temperature values were recorded. This research contributes to fill existing literature gaps on the yearly behaviour of green façades and on the energy benefits these provide.

Nomenclature

BW	Bare wall	HF	Heat flux [W m^{-2}]
CP	Cool and cold period	GF	Green façade
CV	Convective heat transfer [W m^{-2}]	HSR_{cum}	Cumulative solar radiation on the horizontal plane [MJ m^{-2}]
CW	Covered wall		
df	Degrees of freedom	LWIR	Longwave infrared
E	Solar heat transfer [W m^{-2}]	MS	Mean square
EAT	External air temperature [°C]	P	P-value of the F statistic
EP	Energy penalty [MJ m^{-2}]	R	LWIR heat transfer [W m^{-2}]

ERH	External air relative humidity [%]	W	Wind velocity [m s^{-1}]
ES	Energy saving [MJ m^{-2}]	WP	Warm and hot period
F	F statistic		

1 Introduction

Urban areas are in urgent need of transformation to become more sustainable, especially through a wider use of clean energy and more energy efficient buildings (IEA, 2020). The introduction and the spread of urban green infrastructures can be a good solution to this challenge, since these can provide many benefits simultaneously (Miralles I Garcia, 2017; Sharifi, 2021). Among urban green infrastructures, particularly noteworthy are those consisting in the application of vegetation on the building envelope. Apart from many aesthetic and social benefits, greenery systems for buildings provide energy advantages since these are a passive technology useful to improve thermal performance of new and existing buildings (Al-Kayiem *et al.*, 2020; Bevilacqua, 2021; Liao *et al.*, 2021).

Vegetation can be widely applied on the vertical surfaces of buildings according to the different type of vertical greenery systems. Vertical greenery systems provide benefit both at urban scale (mitigation of the urban heat island, promotion of biodiversity, rainwater management, improvement of air quality) and at building scale (energy saving, envelope longevity, reduction of sound transmission, greywater treatment) (Blanco *et al.*, 2018; Susca *et al.*, 2022; Zhang *et al.*, 2019).

The energy aspect and the way vertical greenery systems modify the thermal behaviour of buildings deserve particular attention, especially considering the high energy consumption and environmental impact of buildings. Vertical greenery systems are known as systems able to control heat transfer through the envelope and, consequently, building energy needs, but the real extent of the energy saving (ES) provided needs further investigation.

A typology of vertical greenery systems which could be widely applied is that known as green façade (GF). This is characterized by a simpler design, easier installation and maintenance and lower cost than the other typology, i.e. the living wall (Medl *et al.*, 2017). GFs can be directly attached to the wall, known as direct GFs, or at a certain distance from the envelope, the indirect or double skin GFs. In the latter, there is an air gap between the wall and the vegetation, and a support structure is needed to assist plants growth. Suitable plants can be evergreen or deciduous, climbing or cascading.

Studies on vertical greenery systems suggest that these interact with the building mainly by increasing the envelope thermal insulation, shading, mitigating the air velocity and providing cooling through evapotranspiration. The shading effect and the plant evapotranspiration, responsible for air and wall surface temperature reduction, are particularly effective in warm periods and contribute to reduce cooling demand (Bakhshoodeh *et al.*, 2022; Blanco *et al.*, 2021; Convertino *et al.*, 2021; Lee and Jim, 2019; Zheng *et al.*, 2020). On the other hand, the vegetation, acting as a thermal and wind barrier, provides air and wall surface warming in cold periods (Perini *et al.*, 2011; Xing *et al.*, 2019; Zhao *et al.*, 2022).

Many authors tried to analyse the ES achievable through vertical greenery systems. A 76% reduction of the cooling energy demand was obtained by Wong and Baldwin (Wong and Baldwin, 2016) for deciduous double skin GFs tested in Hong Kong. An ES between 21% and 37% for winter heating was recorded by Cameron *et al.* (2015) in the case of cuboids with evergreen direct GFs at the University of Reading, England. A living wall monitored in Genoa (Italy) allowed Perini et al. (Perini *et al.*, 2017) to record a cooling load reduction of 26%. The simulation carried out by Dahanayake and Chow (Dahanayake and Chow, 2017) of a building equipped with a living wall in Hong Kong and Wuhan (China) highlighted a 3% decrease of the cooling energy demand but an increase of the heating needs. The experimental study by Coma *et al.* (2017) on indirect deciduous GFs and evergreen living walls under Mediterranean climatic conditions showed the achievement of ES during the warm period and no energy penalty (EP) or a slight advantage in the cold period.

Although studies are available on energy performance of vertical greenery systems, many research gaps still exists about that. Most of the research concerns living walls rather than the most feasible solution of the GFs, is focused on the warm period and thus on the cooling performance and lacks long-term experimental data useful to understand the energy behaviour throughout the year (Al-Kayiem *et al.*, 2020; Ascione *et al.*, 2020).

This research aims at providing a contribution to fill the research gaps. The study is focused on the energy functioning of an evergreen GF, analysing it both in warm and cold period, all year round. The results come from a two-year experimental campaign and the ES evaluation is based on the analysis of the heat flux at the covered wall (CW) behind vegetation and at the bare wall (BW) and in particular on the heat flux reduction achieved through the GF. Moreover, it was investigated if and how the ES is influenced by the climatic parameters of the site.

2 Materials and methods

2.1 Study area

The energy functioning of an evergreen GF was studied at the University of Bari. An experimental GF was realized and monitored for two years at the experimental centre in Valenzano (Bari, Italy). The site has latitude 41.0199° N, longitude 16.9048° E, elevation 124 m a.s.l. and is characterized by a typical Mediterranean climate (Cfa (Kottek *et al.*, 2006)).

2.2 Green façade prototype

The GF was realized with evergreen climbing plants of *Rhyncospermum jasminoides*, assisted in their upward growth by a supporting structure placed 0.15 m far from the south oriented wall of the building prototype. A steel frame and a steel net were used as plant-supporting structure, suitable for obtaining a GF that exceeds 3 meters in height. There is not much consensus on the best air gap depth in vertical greenery systems (Hunter *et al.*, 2014). The air layer is generally left open and its thickness is greatly variable (from 0.05 cm up to 60 cm) (Ascione *et al.*, 2020), thus a 0.15 m thickness was chosen to promote the activation of ventilation in the cavity, which can be a desired effect in summertime. *Rhyncospermum jasminoides* has fast growth and its branches can reach lengths around ten meters.

The building prototype has a rectangular plane (4.20 m x 1.50 m) and a height of 2.00 m (Figure 1). To simulate widespread building envelope in Mediterranean area, the south oriented wall was not provided with insulation and was made up of hollow bricks held together with cement mortar and externally finished with white plaster. It has an overall thickness of 0.21 m and an overall thermal resistance of 0.87 K m^2 W^{-1}.

The constructive typology for the wall was chosen since it is the most widespread in the recent buildings heritage of the Mediterranean area. Indeed, the aim of this study was to point out if it is possible to improve the thermal performance of existing walls having high thermal transmittance and no thermal insulation by applying a GF.

2.3 Experimental design and data collection

A part of the wall was left bare, while another part was arranged as a GF. These two parts were thermally separated by interposing embedded panels of extruded polystyrene perpendicularly to the wall plane. The air inside the building prototype was conditioned in the cold period by a fan heater (CH 7000 TURBO Aspira, Fantini Cosmi, Milan, Italy) and in the warm period by a portable heat pump monobloc air conditioner (Ellisse hp, Olimpia Splendid, Cellatica, Italy). A room chronothermostat (C804, Fantini Cosmi, Milan, Italy) allowed managing the internal air temperature. The temperature set point was 20 °C in winter and 26 °C in summer. The energy functioning of the GF was evaluated with reference to the BW, kept as control wall.

A monitoring system consisting of three data loggers (two CR10X and one CR1000 Campbell, Logan, USA) and the sensors was implemented (Figure 1). Measurements were taken every 60 s, averaged every 15 min and stored in the data loggers. The recorded parameters and the corresponding used sensors were: solar irradiation on a horizontal plane, measured by a pyranometer (model 8-48, Eppley Laboratory, Newport, RI, USA); wind speed and direction by a Wind Sentry anemometer (model 03002, R.M. Young Company, USA); indoor and outdoor air temperature and relative humidity through HygroClip-S3 sensors (Rotronic, Zurich, Switzerland); wall surface temperature by thermistors (Tecno.el s.r.l. Formello, Rome, Italy); canopy temperature by means of Apogee SI 400 radiometers (Logan, UT, USA); incoming long-wave infrared (LWIR) radiation on the wall with a PIR pyrgeometer (Eppley Laboratory, Newport, RI, USA); solar radiation behind the vegetation by a pyranometer PIR02 (Geoves s.n.c., Conegliano, Italy); air speed and direction in front of and behind vegetation with an ultrasonic anemometers (ATMOS 22, METER Group, Inc., Pullman, WA, USA).

The collecting of data began in April 2019 and lasted until March 2021. The weather parameters of the period, i.e. cumulative solar radiation on the horizontal plane (HSR_{cum}), external air temperature (EAT), air relative humidity (ERH) and wind velocity (W), are shown in Table 1.

The maximum and minimum values of the monthly HSR_{cum} were recorded in July 2020 and in December 2019, respectively. The mean daily HSR_{cum} values ranged in 4.4-25.7 MJ m^{-2}, and the maximum and minimum values were recorded in July 2020 and in November-December 2020, respectively. EAT maximum and minimum values were recorded in June 2019 and in March 2020, respectively. The lowest value of ERH was recorded in July 2019. W maximum was recorded in November 2019.

2.4 Data analysis

Thanks to the continuously collected data, the GF thermal performance was analysed all year round, in all the seasons and in relation with the period of the day. This allowed to evaluate the ES provided by the GF.

In this research, the ES was evaluated based on the difference in the overall heat transfer through the BW and the CW. This choice was based on the strong connection existing between the thermal performance of the building envelope and the building's energy needs, especially in the case of uninsulated lightweight envelopes like that of the experimental prototype. The heat transfer at the BW (HF_{BW}, W m^{-2}) and at the CW (HF_{CW}, W m^{-2}) included all the heat transfer mechanisms, as follows:

$$HF_{BW} = E_{BW} + R_{BW} + CV_{BW} \tag{1}$$

$$HF_{CW} = E_{CW} + R_{CW} + CV_{CW} \tag{2}$$

where E_{BW} and E_{CW} [W m^{-2}] are the balances of the solar radiative heat exchanges at the BW and CW, respectively, R_{BW} and R_{CW} [W m^{-2}] are the balances of the LWIR radiative heat flows at the BW and CW, respectively; CV_{BW} and CV_{CW} [W m^{-2}] are the balances of the convective heat exchanges at the BW and the CW, respectively. The terms of flux in Eqs. (1)-(2) were calculated starting from the parameters measured during the experimental test, according to Convertino *et al.* (2020) and (2021) and Blanco *et al.* (2021).

For calculating ES, it was distinguished between warm and hot (WP) and cool and cold (CP) periods and between daytime and night-time. Night-time was considered when solar radiation on the horizontal plane was zero. The distinction between WP and CP was made based on the EAT average calculated over 10 days and considering a base temperature of 18 °C. Periods were defined WPs if the mean EAT was above 18 °C and CPs if the mean EAT was below or equal to 18 °C.

The ES was obtained as difference between the overall energy transfer through the BW and that through the CW. It was not directly evaluated as reduction of the energy consumption of the air conditioning system, which was used only to maintain the indoor set-point air temperature. According to the distinction between WPs and CPs, it was analysed if energy gains and losses were desired or not and consequently if there was an ES or an EP. In WPs, ES was provided by the GF if the energy input at the CW was lower than at the BW, while in CPs, ES was achieved if energy output from the CW was lower.

Analysis of variance (ANOVA) is a statistical technique that is used to check if the means of two or more groups are significantly different from each other. The ANOVA can be used to evaluate the variation in a response variable as affected by several factors and levels of the factors. The null hypothesis in ANOVA is true when all the sample means have no significant difference or are equal. When the null hypothesis is rejected, the test does not give information on which means (effects) of a treatment significantly differ from the others. Tukey-Kramer's test is a procedure of multiple comparisons among the means used to find means that statistically differ from each other. A one-way analysis of variance was carried out to assess the influence of daily average EAT on daily ES due to the GF. In case ANOVA showed significant differences, Tukey Kramer's test was performed at a 0.05 significance level to examine the effect of the different levels of EAT. All the statistical analyses were performed with the CoStat software (CoHort Software, Monterey, CA, USA).

3 Results and discussion

3.1 Reduction in wall heat flux

The experimental data were used to calculate and compare the overall heat transfer through the CW and the BW. It was pointed out that the presence of the GF affected boundary conditions and surfaces parameters. In turn variations in heat fluxes were recorded at the two walls and during the year. Such energy transfer changes were considered to assess the ES.

Energy transfer was calculated both for the CW and the BW and either in WPs or CPs. Figure 2 shows the overall heat fluxes and the heat flux components at the two walls together with the solar irradiance on a horizontal plane for a winter (1-3 January 2020), spring (3-5 May 2020),summer (10-12 July 2020) and autumn (20-22 October 2020) period. These periods were chosen since they were representative of the four different seasons and belong to months characterized by the lowest (January), the highest (July) and intermediate values (May and October) of ES provided by the GF. The heat flow oscillated between positive values, i.e. energy input, and negative ones, i.e. energy output. In general, it was observed that the amplitude of the oscillation for the heat flow at the CW was lower than that at the BW. Both walls recorded energy losses at night-time in all the seasons. Higher energy losses were generally obtained for the BW. At daytime, the CW gained always less energy. This general behaviour was observed also looking at the three components of the net flux. The

BW gained more solar radiative energy than the CW. In sunny days, the peak in heat transfer in BW occurred earlier than the solar irradiance peak because solar radiation on a vertical wall occurs earlier than on a horizontal surface. This is demonstrated by the trend of the solar component of the flux that strongly depends on the solar component normal to the wall. LWIR exchanges were generally higher for the BW. Convective heat transfer was generally reduced at the CW, also because of low air velocity in the air gap behind vegetation. In the analysed days, mean air velocity in the gap was in fact equal to 0.77 m s^{-1} in winter, 0.50 m s^{-1} in spring, 0.45 m s^{-1} in summer and 0.42 m s^{-1} in autumn, with the highest value (1.51 m s^{-1}) recorded in January and the lowest (0.12 m s^{-1}) in May. The air flow was mainly upward and from east.

In winter (CP), the heat flow at the BW ranged between -101.71 W m^{-2} and 37.37 W m^{-2}, with a mean value of -32.26 W m^{-2}, while that at the CW ranged between -63.22 W m^{-2} and 6.17 W m^{-2}, with a mean of -29.11 W m^{-2} (Figure 2(a)). In CPs, since the sunlight hours and the solar irradiance are lower, the LWIR radiative and the convective transfer mostly influenced the walls thermal behaviour. The GF positively affected the CW by acting as a barrier in limiting LWIR radiative and convective losses. In summer (WP), the mean value of the heat flow at the BW was -1.28 W m^{-2}, with a minimum value of -51.07 W m^{-2} and a maximum of 95.45 W m^{-2}. At the CW, the heat flow was in the range -44.90 W m^{-2}–22.88 W m^{-2} with a mean of -12.77 W m^{-2} (Figure 2 (b)). In WPs, the effect of the solar radiation is more relevant, and the main advantages provided by the GF are due to the shading effect and the plant evapotranspiration. In spring, the mean value of heat flow was -8.20 W m^{-2}, with a minimum of -53.46 W m^{-2} and a maximum of 88.38 W m^{-2}, for the BW. At the CW, the mean value was 5.85 W m^{-2}, with a minimum of -6.13 W m^{-2} and a maximum of 28.01 W m^{-2}. In autumn, at the BW the heat flow was between -74.68 W m^{-2} and 39.62 W m^{-2}, with a mean of -21.64 W m^{-2}, while at the CW, the values ranged between -42.08 W m^{-2} and 19.46 W m^{-2}, with a mean of -14.13 W m^{-2}. The latter periods (May and October) are intermediate, characterized by the transition from the cold to the hot season and vice versa, thus the positive effects of the GF came from the combination of the thermal barrier effect, and shading and evapotranspiration.

In this study, the ES was considered and calculated in terms of reduction of the heat flow from inside to outside through the CW in CPs and from outside to inside through the CW in WPs, compared with the BW. Instantaneous values of the heat flux reduction are shown in Figure 3. Overall, ES was obtained both in CPs and in WPs, in the four seasons.

In winter (CP) when the mean EAT was 8.25 °C, the ES value reached 52.85 W m^{-2}, with a mean value of 3.23 W m^{-2} and a maximum EP of 38.66 W m^{-2} (Figure 3 (a)). The ES was mainly obtained in the second half of the day, while the GF implied an EP in the morning.

In spring, when the mean EAT recorded was 17.36 °C, the ES reached a maximum of 49.85 W m^{-2}, the EP was up to 57.14 W m^{-2} and on average an ES of 4.75 W m^{-2} was obtained (Figure 3 (b)). ES was generally obtained except for the morning.

In summer (WP), with a mean EAT of 25.31 °C, the ES was up to 72.56 W m^{-2}, with a mean of 11.47 W m^{-2} and an EP up to 16.70 W m^{-2} (Figure 3 (c)). In this case, ES was higher than during CP and was achieved almost throughout the day with some exceptions in the evening and at night-time.

In autumn, with a mean EAT equal to 13.96 °C, a mean ES of 7.51 W m^{-2} was achieved. The highest ES value was 34.47 W m^{-2}, while the highest EP was 26.03 W m^{-2}. In this period, the GF guaranteed ES almost all day, EP was limited to the morning.

The analysed representative winter period (CP) and summer period (WP) were selected from the months in which the lowest (January) and the highest (July) ES were recorded. The spring and autumn periods were selected in those months considered of transition from CP to WP and vice versa. Following the proposed calculation method for ES and by integrating the values over time, this was determined for each month of the year, obtaining a mean value of 8.19 MJ m^{-2} per month and an annual ES of 98.27 MJ m^{-2} (Figure 4). As shown for the analysed periods (Figure 3), also the annual trend of the ES suggested that the GF provided higher advantages in warmer months than in colder ones (Figure 4 (a)). The negative effects induced at daytime in CPs and at night-time in WPs were offset by the positive ones in the rest of the day. As demonstrated in more detail in a previous study by Vox *et al.* (2022), the EP is always compensated by the ES not only in warm months but also in cold ones. Finally, an ES was obtained not only annually, but also in every month of the year, although to different extents. Analysing the ES with reference to the time of the day, it was shown that the maximum ES was obtained at daytime, with an annual value of 70.87 MJ m^{-2}, a high value (53.89 MJ m^{-2}) was also obtained at night-time (Figure 4 (b)). During daytime it was also obtained the highest EP (23.77 MJ m^{-2}), while a lower value of 2.72 MJ m^{-2} was recorded at night (Figure 4 (b)).

In this study we proposed the evaluation of the ES provided by an evergreen double-skin GF as overall heat flux reduction. This choice was driven by the close connection between the thermal performance of the envelope and the building energy needs for heating/cooling. Other authors analysed the ES provided by greenery systems by focusing on the energy consumptions for building air conditioning. The findings of our study can be qualitatively compared with those in literature and are consistent with these. Many authors found that the application of a greenery system reduced cooling energy demand (Coma *et al.*, 2017; Kontoleon and Eumorfopoulou, 2010; Perini *et al.*, 2017). Advantages achieved thanks to the greenery were reported also with reference to the heating period (Coma *et al.*, 2017; Djedjig *et al.*, 2016; Xing *et al.*, 2019).

3.2 Effect of the external air temperature on the energy saving

The effect of the climatic parameters, i.e. EAT, ERH, HSR_{cum} and W, on the daily ES provided by the GF during the two-year experimental campaign was studied by a statistical analysis.

Firstly, a correlation analysis was carried out for evaluating the degree of association between different pairs of the climatic parameters (explanatory variables). Daily average ERH and HSR_{cum} were moderately correlated ($r > 0.5$) with the daily average EAT (negatively and positively, respectively). W was weakly correlated with EAT, but W was weakly correlated also with ES. Therefore, only EAT was further investigated as factor influencing ES for the ANOVA analysis.

In order to define how and which EAT levels influence ES, an analysis of the overall variance (ANOVA) was performed for each data set, i.e. daytime, night-time and whole day. Table 2 shows the results of the ANOVA concerning EAT influence on the daily mean ES.

The degree of freedom (df) of the factor (source of variation), the mean square (MS), the F statistic (F) and the P-values are presented. MS is the Sum of Squares of the variation of ES attributed to a given source of variation, divided by df. The F statistic is used for determining the significance of variation from different sources. A large F indicates that there is a large variation in ES due to the given source compared to that due to unconsidered sources. P represents the probability that this variation is due to chance alone. Considering a 0.05 level of significance, a P value lower or equal to 0.05 indicates that the given factor or interaction of factors is a statistically significant source of variation for ES.

ANOVA revealed that EAT can be considered a statistically significant source of variation (Table 2).

Tukey Kramer’s test was applied to compare the ES mean values obtained with different levels of EAT (Table 3).

Above 20 °C, the increase of EAT influenced the ES with an increasing positive trend in daytime. The maximum value of the daily average ES (0.60 MJ m^{-2}) was recorded for EAT higher than 28 °C.

At night-time, Tukey Kramer's test recorded a general low variability of the ES in relation to the different levels of EAT (Table 3), however highlighting greater ES below 12 °C.

Overall, higher ES provided by GF is mainly shown in conjunction with extreme values of EAT. This highlighted the benefit deriving from the green layer shading effect, in daytime, and the thermal barrier effect of the GF during night-time.

These findings are consistent with those of Susorova *et al.* (2013). They simulated the performance of a vegetated south exposed exterior façade in a hot humid continental summer climate and found an increasing performance of the green façade in passive cooling as the solar irradiation increased. This agrees with our findings because we found that HSR_{cum} was highly and positively correlated with EAT. Instead, Cheng *et al.* (2010) reported that a vegetated cladding system, tested on a west-southwest wall in late summer in a humid subtropical climate, affected the heat flow mainly in response to solar irradiation rather than to other weather parameters. Coma *et al.* (2017) reported that the outside air temperature showed no correlation with the energy performance of a double-skin GF, installed on the east, south and west facades of an experimental cubicle under Mediterranean continental climatic conditions.

4 Conclusions

This study analysed the thermal performance of an evergreen green façade applied under Mediterranean climate conditions. The benefits deriving from the application of the green façade were assessed by comparing the thermal behaviour of the covered wall, behind vegetation, and that of a bare wall, without greenery.

The analysis was based on experimental data collected over a long-term experimental campaign and on the analytical quantification of the energy saving provided by the green façade. The energy saving was calculated as heat flux reduction through the vegetated envelope, since the envelope thermal performance directly affects the building energy requirements. It was taken into consideration not only the warm period but also the cold one and the overall annual energy functioning. The influence of the climatic parameters on the energy saving provided by the green façade was also investigated by performing a statistical analysis.

The obtained results suggested the advantages of applying an evergreen green façade in Mediterranean areas. In fact, an energy saving was recorded both in warm and in cold periods and in general all over the year. According to the season, energy saving was achieved in different times of the day and the energy penalty obtained was offset by the positive effect. These findings can be considered consistent with those in literature, which highlight that the application of a greenery system is useful for reducing the cooling energy demand (Wong and Baldwin, 2016; Cameron *et al.*, 2015; Perini *et al.*, 2017; Coma *et al.*, 2017) and the heating energy demand (Coma *et al.*, 2017; Xing *et al.*, 2019), and for providing net energy benefits in warm temperature climates (Dahanayake and Chow, 2017). The statistical analysis pointed out that the external air temperature positively influenced the energy saving especially at daytime.

This research represents a contribution to the knowledge of the thermal behaviour of evergreen green façades and of the benefits provided throughout the year, in Mediterranean area. The results of this study are useful for developing an energy model tool to simulate the behaviour of buildings equipped with green façades.

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References

Al-Kayiem H.H., Koh K., Riyadi T.W.B., Effendy M. 2020. A comparative review on greenery ecosystems and their impacts on sustainability of building environment. Sustainability 12(20):1–26. https://doi.org/10.3390/su12208529

Ascione F., De Masi R.F., Mastellone M., Ruggiero S., Vanoli G.P. 2020. Green Walls, a Critical Review: Knowledge Gaps, Design Parameters, Thermal Performances and Multi-Criteria Design Approaches.

Energies 13(9):2296. https://doi.org/10.3390/en13092296

Bakhshoodeh R., Ocampo C., Oldham C. 2022. Evapotranspiration rates and evapotranspirative cooling of green façades under different irrigation scenarios. Energy Build. 269:113323. https://doi.org/10.1016/J.ENBUILD.2022.112223

Bevilacqua P. 2021. The effectiveness of green roofs in reducing building energy consumptions across different climates. A summary of literature results. Renew. Sust. Energ. Rev., 151:111523. https://doi.org/10.1016/J.RSER.2021.111523

Blanco I., Convertino F., Schettini E., Vox G. 2021. Energy analysis of a green façade in summer: an experimental test in Mediterranean climate conditions. Energy Build. 245:111076. https://doi.org/10.1016/j.enbuild.2021.111076

Blanco I., Schettini E., Scarascia Mugnozza G., Vox G. 2018. Thermal behaviour of green façades in summer. J. Agric. Eng. 49(3):183–190. https://doi.org/10.4081/JAE.2018.835

Cameron R.W.F., Taylor J., Emmett M. 2015. A Hedera green façade - Energy performance and saving under different maritime-temperate, winter weather conditions. Build Environ. 92:111–121. https://doi.org/10.1016/j.buildenv.2015.04.011

Cheng C.Y., Cheung K.K.S., Chu L.M. 2010. Thermal performance of a vegetated cladding system on facade walls. Build Environ. 45(8):1779–1787. https://doi.org/10.1016/j.buildenv.2010.02.005

Coma J., Pérez G., de Gracia A., Burés S., Urrestarazu M., Cabeza L.F. 2017. Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades. Build Environ. 111:228–237. https://doi.org/10.1016/j.buildenv.2016.11.014

Convertino F., Vox G., Schettini E. 2020. Thermal barrier effect of green façades: Long-wave infrared radiative energy transfer modelling. Build Environ. 177: 106875. https://doi.org/10.1016/j.buildenv.2020.106875

Convertino F., Vox G., Schettini E. 2021. Evaluation of the cooling effect provided by a green façade as nature-based system for buildings. Build Environ. 203:108099.

https://doi.org/10.1016/J.BUILDENV.2021.108099

Dahanayake K.W.D.K.C., Chow C.L. 2017. Studying the potential of energy saving through vertical greenery systems: Using EnergyPlus simulation program. Energy Build. 138:47–59. https://doi.org/10.1016/j.enbuild.2016.12.002

Djedjig R., Bozonnet E., Belarbi R. 2016. Modeling green wall interactions with street canyons for building energy simulation in urban context. Urban Clim. 16:75–85. https://doi.org/10.1016/j.uclim.2015.12.003

Hunter A.M., Williams N.S.G., Rayner J.P., Aye L., Hes D., Livesley S.J. 2014. Quantifying the thermal performance of green façades: A critical review. Ecol. Eng. 63:102-113. https://doi.org/10.1016/j.ecoleng.2013.12.021

IEA. (2020). The Covid-19 Crisis and Clean Energy Progress – Analysis - IEA. https://www.iea.org/reports/the-covid-19-crisis-and-clean-energy-progress/buildings#abstract

Kontoleon K.J., Eumorfopoulou E.A. 2010. The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. Build Environ. 45(5):1287–1303. https://doi.org/10.1016/J.BUILDENV.2009.11.013

Kottek M., Grieser J., Beck C., Rudolf B., Rubel F. 2006. World map of the Köppen-Geiger climate classification updated. Meteorol. Zeitschrift, 15(3):259–263. https://doi.org/10.1127/0941-2948/2006/0130

Lee L.S.H., Jim C.Y. 2019. Energy benefits of green-wall shading based on novel-accurate apportionment of short-wave radiation components. Appl. Energy 238:1506–1518. https://doi.org/10.1016/j.apenergy.2019.01.161

Liao J., Tan X., Li J. 2021. Evaluating the vertical cooling performances of urban vegetation scenarios in a residential environment. J. Build. Eng. 39:102313. https://doi.org/10.1016/j.jobe.2021.102313

Medl A., Stangl R., Florineth F. 2017. Vertical greening systems – A review on recent technologies and research advancement. Build Environ. 125:227–239. https://doi.org/10.1016/j.buildenv.2017.08.054

Miralles I Garcia J.L. 2017. Strategic environmental assessment for metropolitan plans of coastal areas. The case of Valencia. Int. J. Sustain. Dev. 12(8):1272–1281. https://doi.org/10.2495/SDP-V12-N7-1272-1281

Perini K., Bazzocchi F., Croci L., Magliocco A., Cattaneo E. 2017. The use of vertical greening systems to reduce the energy demand for air conditioning. Field monitoring in Mediterranean climate. Energy Build. 143:35–42. https://doi.org/10.1016/j.enbuild.2017.03.036

Perini K., Ottelé M., Fraaij A.L.A., Haas E.M., Raiteri R. 2011. Vertical greening systems and the effect on air flow and temperature on the building envelope. Build Environ. 46:2287–2294. https://doi.org/10.1016/j.buildenv.2011.05.009

Sharifi A. 2021. Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review. Sci. Total Environ. 750:141642. https://doi.org/10.1016/j.scitotenv.2020.141642

Susca T., Zanghirella F., Colasuonno L., Del Fatto V. 2022. Effect of green wall installation on urban heat island and building energy use: A climate-informed systematic literature review. Renew. Sust. Energ. Rev. 159:112100. https://doi.org/10.1016/j.rser.2022.112100

Susorova I., Angulo M., Bahrami P., Brent S. 2013. A model of vegetated exterior facades for evaluation of wall thermal performance. Build Environ. 67:1–13. https://doi.org/10.1016/j.buildenv.2013.04.027

Vox G., Blanco I., Convertino F., Schettini E. 2022. Heat transfer reduction in building envelope with green façade system: A year-round balance in Mediterranean climate conditions. Energy Build. 274: 112439. https://doi.org/ 10.1016/j.enbuild.2022.112439

Wong I., Baldwin A.N. 2016. Investigating the potential of applying vertical green walls to high-rise residential buildings for energy-saving in sub-tropical region. Build Environ. 97:34–39. https://doi.org/10.1016/j.buildenv.2015.11.028

Xing Q., Hao X., Lin Y., Tan H., Yang K. 2019. Experimental investigation on the thermal performance of a vertical greening system with green roof in wet and cold climates during winter. Energy Build. 183:105–117. https://doi.org/10.1016/J.ENBUILD.2018.10.038

Zhang C., Wang J., Li L., Gang W. 2019. Dynamic thermal performance and parametric analysis of a heat recovery building envelope based on air-permeable porous materials. Energy 189. https://doi.org/10.1016/j.energy.2019.116361

Zhao C., Zhang L., Yang Y., Zhang Y., Liu M., Yan J., Zhao L. 2022. Long-wave infrared radiation properties of vertical green façades in subtropical regions. Build Environ. 223:109518. https://doi.org/10.1016/J.BUILDENV.2022.109518

Zheng X., Dai T., Tang M. 2020. An experimental study of vertical greenery systems for window shading for energy saving in summer. J. Clean. Prod. 259:120708. https://doi.org/10.1016/j.jclepro.2020.120708

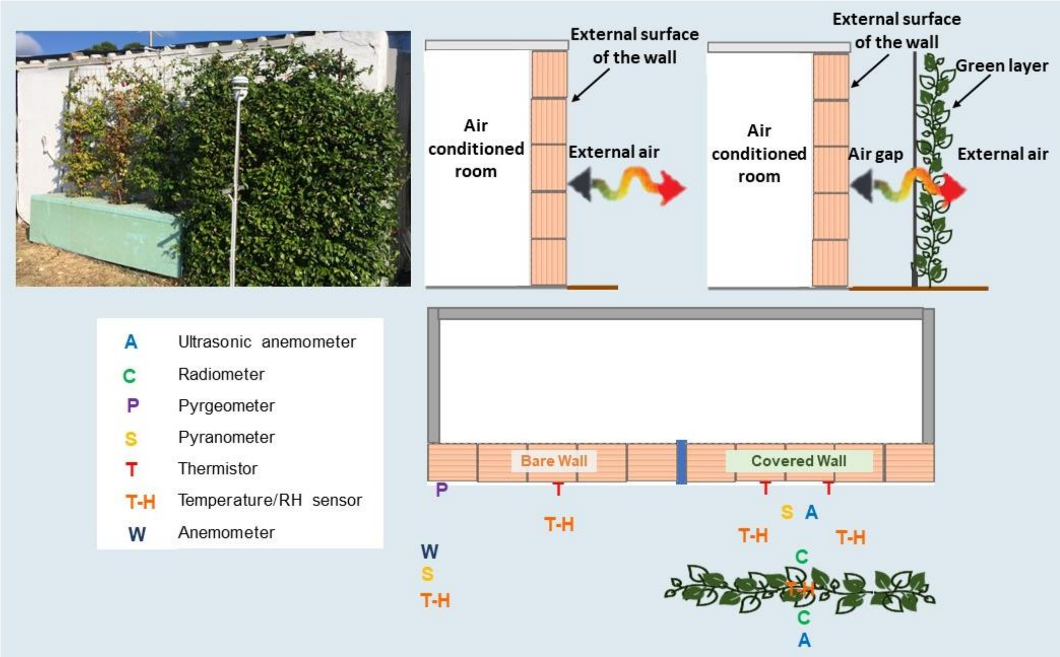
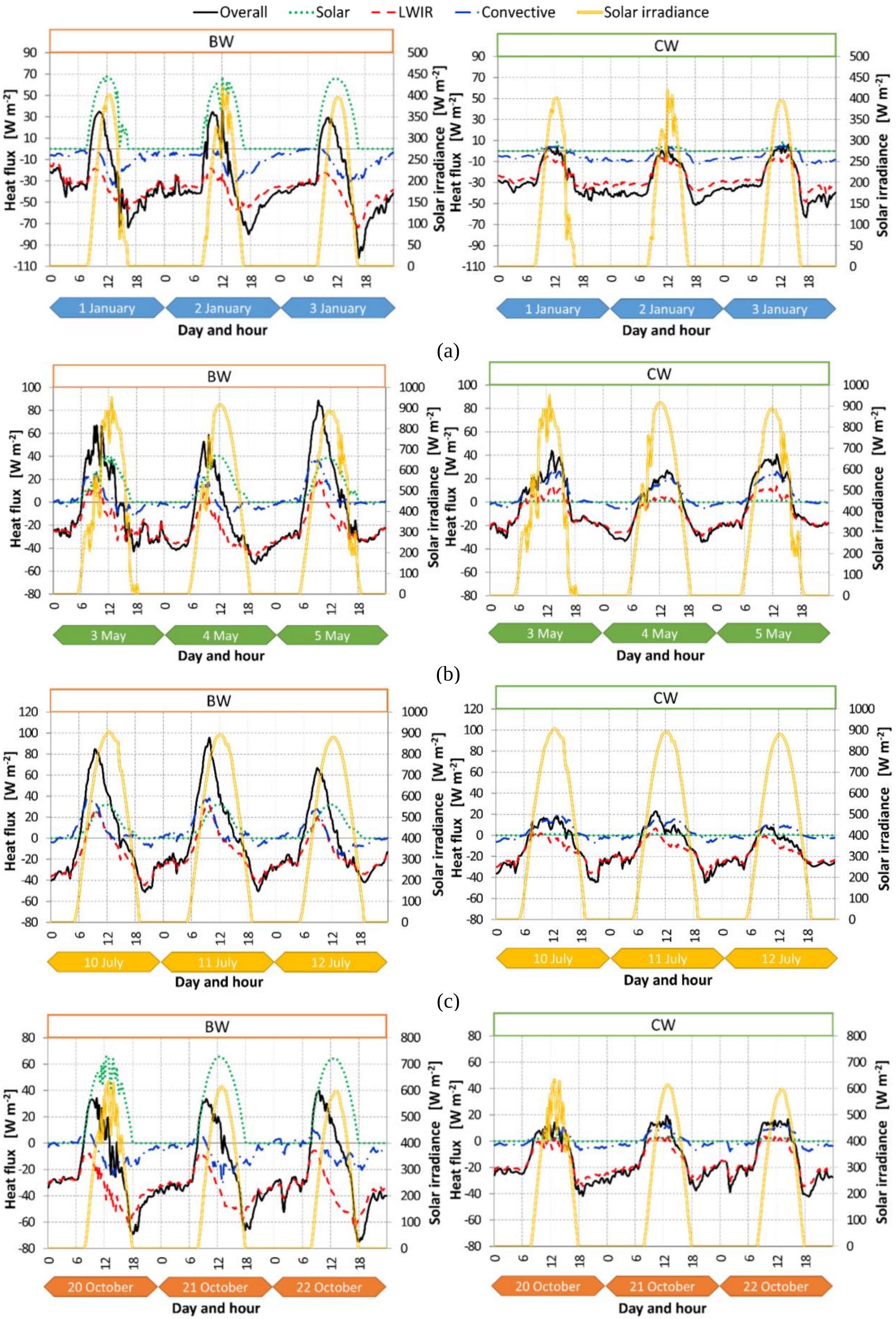


Figure 1. Experimental prototype: vertical sections of the bare and covered wall with layers; horizontal section with sensors.

Overall
Solar
LWIR
Convective
Solar irradiance
BW
CW
Heat flux [W m^{-2}]
Solar irradiance [W m^{-2}]
Day and hour
1 January
2 January
3 January
3 May
4 May
5 May
10 July
11 July
12 July
20 October
21 October
22 October
0
6
12
18

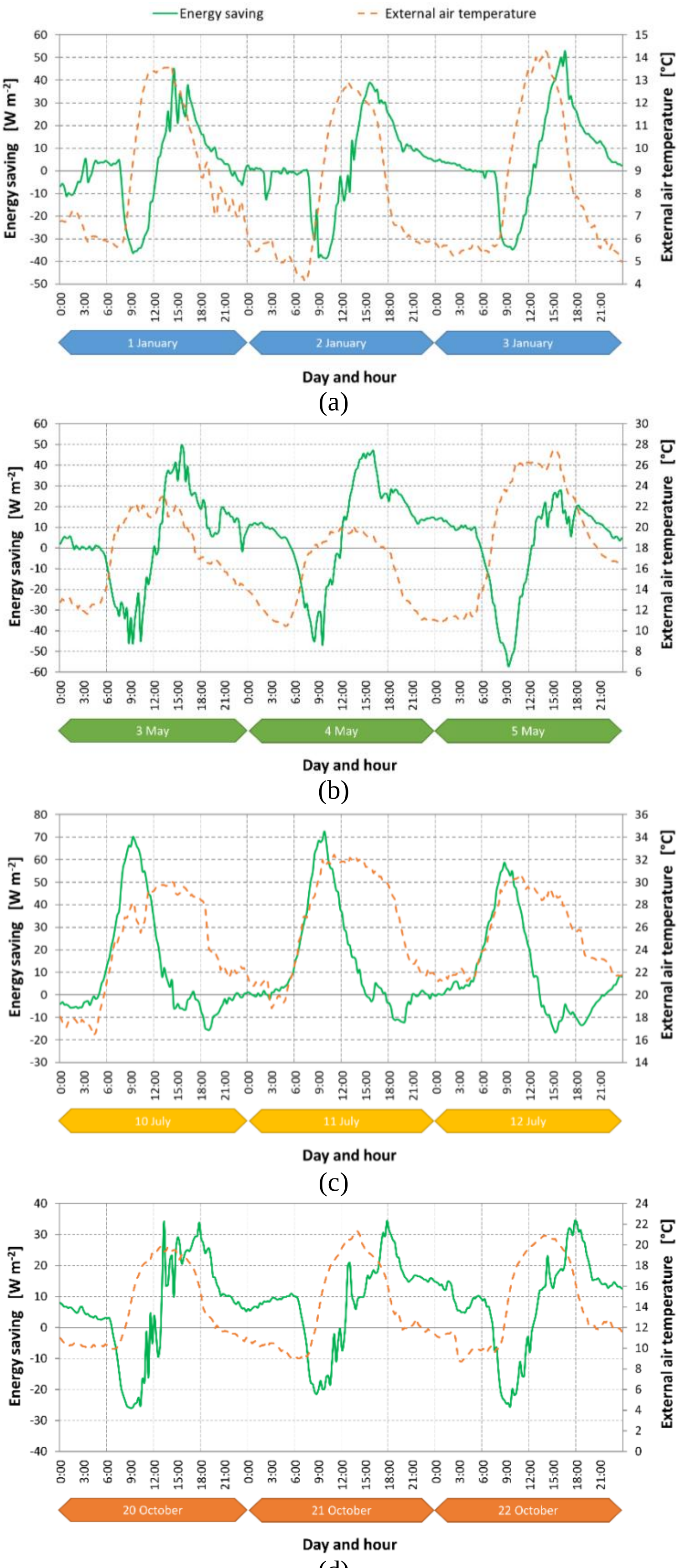
(a)

(b)

(c)

(d)

Figure 2. Heat fluxes at the bare (BW) and covered (CW) wall in winter (a), spring (b), summer (c) and autumn (d): overall values, solar, LWIR and convective heat flux components (primary axis) and solar irradiance on a horizontal plane (secondary axis).



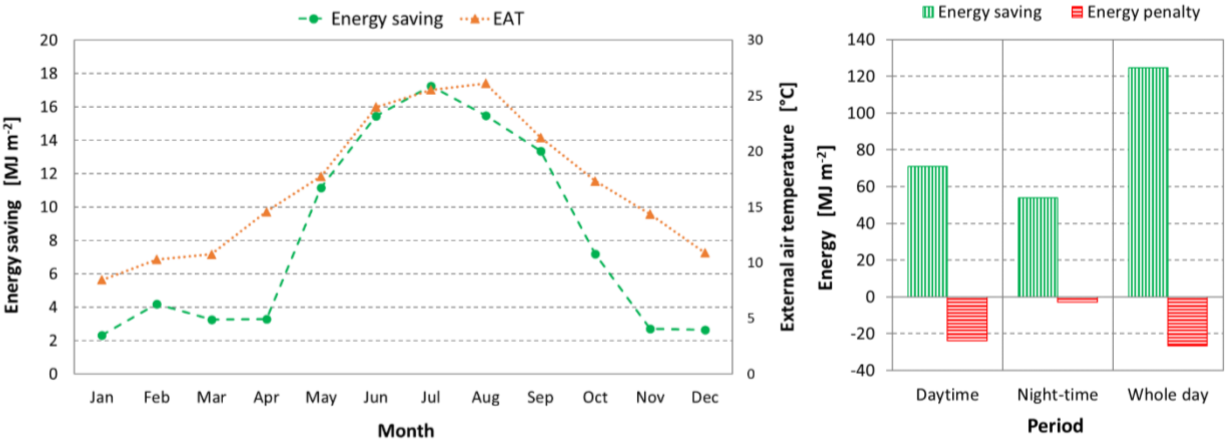
(a)

(b)

(c)

(d)

Figure 3. Energy saving, as heat flux reduction, provided by the green façade (primary axis) and external air temperature (secondary axis) in winter (a), spring (b), summer (c) and autumn (d).



(a) (b)

Figure 4. Monthly mean energy saving provided by the green façade (primary axis) and monthly mean external air temperature (secondary axis) (a); average annual energy saving and energy penalty according to the day period (b).

Table 1. Weather parameters of the site recorded during the testing period (April 2019-March 2021).

Month	Daily HSR_{cum} [MJ m^{-2}]			Monthly HSR_{cum} [MJ m^{-2}]	EAT [°C]			ERH [%]			W [m s^{-1}]	
	mean	min	max		mean	min	max	mean	min	max	mean	max
Apr-2019	15.1	2.3	24.1	454.5	14.6	7.6	27.6	72.0	28.6	97.5	2.2	8.4
May-2019	17.6	3.1	27.2	546.4	16.6	5.8	26.2	70.3	32.4	97.4	2.1	7.2
June-2019	25.7	18.4	27.6	770.5	26.1	12.9	38.4	54.0	19.2	94.9	1.8	4.4
Jul-2019	23.5	7.4	27.3	727.1	26.2	17.2	37.9	55.1	14.9	96.9	1.9	6.7
Aug-2019	21.7	15.4	25.3	672.1	26.8	18.1	38.2	58.1	22.6	96.8	1.7	4.0
Sept-2019	15.4	5.7	19.4	463.4	22.8	12.8	32.5	68.6	30.9	95.6	1.7	4.6
Oct-2019	11.5	4.0	16.0	355.3	18.8	9.6	30.4	75.4	28.2	99.3	1.5	4.4
Nov-2019	6.0	0.5	9.9	180.5	15.7	8.8	26.1	75.5	38.2	99.6	2.1	9.1
Dec-2019	4.4	0.3	8.1	136.0	11.4	2.3	19.5	75.7	37.5	100.0	2.1	8.7
Jan-2020	6.8	1.4	9.9	211.4	9.0	1.8	18.5	76.3	31.3	98.9	1.8	6.5
Feb-2020	9.9	0.8	14.0	287.2	10.9	2.4	24.5	65.8	28.4	98.8	2.0	6.9
Mar-2020	12.8	2.9	18.7	396.4	11.3	-0.4	25.5	71.9	28.4	100.0	1.2	7.9
Apr-2020	17.9	2.0	24.7	537.4	14.6	2.1	26.7	63.1	19.6	100.0	1.7	5.0
May-2020	20.0	5.0	28.2	619.3	19.0	10.4	33.3	62.6	15.4	99.9	1.8	7.9
June-2020	23.2	1.5	28.5	697.0	21.8	12.2	34.0	61.5	24.1	100.0	1.8	6.6
Jul-2020	25.4	14.3	28.6	788.6	24.8	16.4	36.7	56.3	20.9	97.6	1.7	5.2
Aug-2020	21.5	8.6	26.1	667.1	25.4	18.3	38.2	60.9	25.1	94.9	1.8	5.0
Sept-2020	16.3	7.4	21.5	490.2	19.7	6.1	31.7	69.4	32.1	95.0	1.7	6.0
Oct-2020	11.1	1.6	16.2	345.0	15.8	6.3	28.5	77.9	33.1	100.0	1.9	7.2
Nov-2020	6.6	0.1	10.8	197.2	13.0	5.6	21.2	89.8	42.7	100.0	1.5	5.2
Dec-2020	4.6	0.1	7.8	143.7	10.3	4.1	18.8	87.8	46.2	100.0	1.9	7.4
Jan-2021	5.5	0.4	10.4	170.1	7.9	-0.1	18.4	79.4	23.0	100.0	2.0	7.2

Feb-2021	9.5	1.0	14.5	265.9	9.6	1.0	20.0	75.0	31.5	100.0	2.0	6.7
Mar-2021	13.5	2.4	20.4	418.2	10.2	1.9	21.4	67.3	29.4	96.8	1.9	6.5

Table 2. External air temperature (EAT) influence on the energy saving during the whole day, at daytime and night-time (ANOVA).

	Source		**df**	**MS**	**F**	**P**
Whole day	Main Effect	EAT	6	6.67	48.79	***
	Error		1019	0.14		
Daytime	Main Effect	EAT	5	9.82	63.95	***
	Error		507	0.15		
Night-time	Main Effect	EAT	5	1.03	11.49	***
	Error		507	0.09		

*** $P \leq 0.001$

Table 3. Mean values of the daily energy saving during the whole day, at daytime and night-time, as a function of EAT levels (Tukey-Kramer’s test).

<table>
<tr><th></th><th colspan="7">EAT [°C]</th></tr>
<tr><th></th><th>EAT < 8</th><th>8 < EAT ≤ 12</th><th>12 < EAT ≤ 16</th><th>16 < EAT ≤ 20</th><th>20 < EAT ≤ 24</th><th>24 < EAT ≤ 28</th><th>EAT > 28</th></tr>
<tr><td>ES [MJ m^{-2}] – whole day</td><td>0.21^{c}</td><td>0.10^{c}</td><td>-0.02^{d}</td><td>-0.02^{d}</td><td>0.15^{c}</td><td>0.39^{b}</td><td>0.69^{a}</td></tr>
<tr><td rowspan="2">ES [MJ m^{-2}] - daytime</td><td colspan="2">EAT ≤ 12</td><td rowspan="2">-0.12^{d}</td><td rowspan="2">-0.04^{d}</td><td rowspan="2">0.28^{c}</td><td rowspan="2">0.51^{b}</td><td rowspan="2">0.69^{a}</td></tr>
<tr><td colspan="2">-0.12^{d}</td></tr>
<tr><td rowspan="2">ES [MJ m^{-2}] - night-time</td><td rowspan="2">0.27^{a}</td><td rowspan="2">0.21^{a}</td><td rowspan="2">0.08^{b}</td><td rowspan="2">0.00^{b}</td><td rowspan="2">0.04^{b}</td><td colspan="2">EAT > 24</td></tr>
<tr><td colspan="2">0.01^{b}</td></tr>
</table>

[a-b-c-d] Mean values of energy saving ES in a row with a different superscript letter statistically differ at $P \leq 0.05$ using Tukey-Kramer’s test.