THERMAL BEHAVIOUR OF GREEN FAÇADES IN WINTER CLIMATIC CONDITIONS

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ABSTRACT

Green infrastructures inside cities represent an effective strategy to face with the increasingly urgent environmental problems. Green systems applied to building envelope are among the most applicable and useful solutions. These provide many significant advantages at different scales. Green façades (GF) are a typology of vertical green systems, applied to the vertical components of the building envelope. GF allow to save energy for air conditioning, by improving the envelope thermal performances. Energy behaviour of GF has been more deeply studied in warm periods, than in cold ones. This paper aims to analyse wintertime energy performances of GF. Evaluations were carried out based on the experimental data collected on two GF, in Bari (Italy), under Mediterranean climatic conditions. The experimental set-up included also a bare wall (BW), used as control. The heating effect provided by the greenery was pointed out through statistical and energy analyses. At night-time, the covered walls (CW) were warmer than the bare one up to 3.5°C. The dependence of night-time heating effect on microclimate parameters, as external air temperature, relative humidity and wind speed, was studied. External air temperature was found to be the most influencing factor: as it dropped, the heating effect increased. Overall energy transfer through the CW was lower than through the BW at night-time. The long-wave infrared energy radiative losses were reduced thanks to the green layer, which acted as a thermal barrier. These findings proved that GF improve winter night-time thermal performance by reducing energy losses.

Keywords: energy saving, energy transfer, green infrastructure, heating effect, thermal barrier, vertical greening.

1 INTRODUCTION

The United Nations report the estimates and the projections of urban and rural populations in all parts of the world [1, 2]. In 2019, urban settlements worldwide have housed 55.7% of the population [2]. By 2030, a projection of 60% of people globally will be concentrated in cities, and 28% of people will live in cities with at least 1 million inhabitants [1]. When rural or natural areas are transformed into urban settlements, vegetation is replaced by non-green manufacts as streets and buildings. This replacement contributes to the global climate change, which is reflected by the urban heat island (UHI) effect, and produces negative effects such as acoustic and air pollution, flooding or drought and inadequate rainwater management [3]. These impacts will influence citizens health and wellbeing [4]. This awareness led to the Goal 11 of the United Nations 2030 Agenda for Sustainable Development [5] which is a commitment by 2030 to make cities and human settlements inclusive, safe, resilient and sustainable in all countries.

Sustainability can be realized in urban contexts by the application of the greening technology. Urban green infrastructures (UGIs) include parks, gardens, grassy verges, urban trees and hedges, and vegetated systems such as green walls and roofs. The type of UGI to be applied depends

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on the climate of the region, the characteristics of plant and soil, the water availability but also on investment, community norms and cultural values [6].

UGIs can be used to reduce the impact of the UHI through cooling effects like shading and transpiration. UGIs interact with the surrounding urban environment; their dynamic parameters should be considered, and all heat and mass exchanges must be taken into account in their modelling [7–11]. UGIs have multiple environmental, social and economic benefits that help to improve buildings and cities sustainability [12].

The use of vegetated horizontal and vertical greenery systems (VGSs) is a sustainable technology for improving energy efficiency of buildings in order to reduce energy consumption for air conditioning in summer and to increase thermal insulation in winter [13–19].

VGSs are a more appropriate solution for tall building typologies due to a high wall to roof ratio. VGSs are classified as green façades (GFs) or living walls (LWs) based on where the plants are placed. Concerning GFs, plants are rooted in the ground or in pots at different heights of the façade, climbing directly on the façade of the building or on a structural support placed at a short distance from the wall. LWs are composed of pre-cultivated panels, modules, or planted bags, fixed to a wall or free-standing frame. The gap between the building and the green wall, ranging from 3 cm to 15 cm, acts as a thermal buffer. This improves building thermal insulation.

In the literature there are more results concerning GFs thermal performance in summer period rather than the whole year [13,20–22]. Research is often carried out on customized and scaled-down closed environments or rooms rather than on real buildings thermally controlled [23]. Some authors presented experimental data concerning only short summer periods [20,24–26]. In summer the performance of the greenery systems has been assessed while their efficacy in winter requires further research due to their dependence on climatic conditions [27].

During wintertime, passive warming may be due to higher temperatures of the air gap and of the wall external surface in GF systems [28,29].

Cameron et al. [30] reported highest thermal performances of GFs during cold periods in temperate oceanic climatic regions, characterized by very low temperatures, high wind or heavy rain. A façade greened with *Hedera helix* recorded wall surface temperatures higher up to 3°C, compared with a bare wall (BW) with an energy saving up to 50%.

Bolton et al. [31] evaluated wall temperatures and energy losses during a test where it was compared a *Hedera helix* GF with a BW, both north facing. This test was carried out in a region characterized by a maritime temperate climate. The difference between the minimum external wall temperatures evaluated on the GF and on the BW was on average 1.7°C; a reduction of winter heating costs was assessed, and energy losses were lowered by almost 8%, despite the heating effect of short-wave radiation was minimized during daytime [31].

In cold periods GFs could lead to an increase of energy consumption for heating due to the shading of solar radiation hitting the building walls [32]. The thermal benefits of GFs in wintertime and the identification of suitable plant species for this application in Mediterranean regions, characterized by high levels of solar radiation, should be assessed [17]. In the recent years new methods for improving sensor reliability and accuracy have been developed, and trusted and accurate estimates of microclimatic parameters can now be measured with advanced low-cost sensors [33–35].

This paper reports the experimental results on the thermal performance of two GF prototypes set at the university of Bari, southern Italy, during wintertime. The façades were greened with two species of plants, these being climbing, evergreen and suitable for the Mediterranean area. During the experimental test, climatic data and surface temperatures were recorded; these data are useful to evaluate the influence of climatic parameters on the heating effect provided by GFs. Evaluations of the effects on the heat transfer induced by the presence of the vegetation layer are also useful to understand the wintertime thermal performance of GFs. The evaluation of the winter behaviour of an evergreen GF represents a novelty, helping to fill the existing gap in the literature concerning GFs. Research on GFs energy behaviour has been focused mainly on warm periods.

2 MATERIALS AND METHODS

Thermal behaviour of GFs and their influence on building envelope performance are affected by the climatic conditions of the surrounding environment.

GFs thermal functioning in winter was analysed by resorting to the analysis of experimental data. Statistical analyses were carried out to evaluate the relationships between climatic parameters and heating effect provided by the GFs. Energy analyses of the heat fluxes occurring in the BW and covered walls (CW) were performed to assess if and how vegetation influences energy transfer in wintertime.

2.1 The experimental test

Experimental data were gathered during a measurement campaign conducted from June 2014 to December 2016 at the University of Bari. Data continuously collected during winter months 2015 and 2016, i.e. December, January and February, were considered. The experimental site is in Valenzano (Bari, Italy) and has latitude 41°01′N and longitude 16°54′E. This is characterized by a Mediterranean climate, classified as Csa by Köppen-Geiger [36]. The main characteristics are a warm temperate climate with an average annual temperature of 16.1°C, seasonal change in solar radiation intensity and rain precipitations mainly in winter months.

The experimental set-up consisted of three small blocks, two used for testing GF application and one as control (Fig. 1). The attention was focused on the south facing walls of the blocks. These were realized in order to replicate a constructive solution widespread in Mediterranean contexts. The walls, having width of 1.00 m, height of 1.55 m and overall thickness of 0.22 m, were made of perforated bricks held together with cement mortar and finished with 0.02 m white plaster. The other walls and roofs were made of expanded polystyrene panels and were shaded by the incident solar radiation through a shading net.

The green layers (GLs) of the two GFs were made one with *Pandorea jasminoides variegated* and the other with *Rhyncospermum jasminoides*, two evergreen climbing species

Figure 1: Experimental set up at the University of Bari: bare wall and green façades with *Pandorea jasminoides* and *Rhyncospermum jasminoides* (from left to right).

suitable for the site climate. In both cases, an iron net was placed at 15 cm from the wall to support the plants growth. The three blocks were not air conditioned.

Several parameters were measured. To this end many sensors were used: hygroclip-S3 sensors (Rotronic, Zurich, Switzerland) for external air temperature and relative humidity, with an accuracy of ±0.1°C and ±0.8%, respectively; thermistors with an accuracy of ±0.15°C (Tecno.EL s.r.l. Formello, Rome, Italy) for walls surface temperature; pyranometers with an accuracy of 10 W m^{-2} (model 8-48, Eppley Laboratory, Newport, RI, USA) for solar radiation (in the wavelength range 300–3000 nm) on horizontal and vertical plane; a Wind Sentry anemometer (model 03002, R. M. Young Company, USA) for wind speed and direction, with an accuracy of 0.5 ms^{-1} and of ±5°, respectively.

Data were measured every 60 s, averaged every 15 min and stored in the data logger (CR10X, Campbell, Logan, USA).

2.2 Statistical analysis

Statistical analysis was performed to assess the influence of the climatic parameters on the winter thermal behaviour of the GFs. The attention was focused on the external air temperature ($T_{ext,a}$), relative humidity ($RH_{ext,a}$) and wind speed (w). The statistical evaluation was based on the analysis of variance (ANOVA) and was carried out by using the CoStat software (CoHort Software, Monterey, CA, USA).

2.3 Energy analysis

Heat fluxes occurring in the two GFs and in the BW were analysed and compared.

2.3.1 Overall heat flux through the walls

To evaluate the overall effect provided by the GF, the conductive heat flux through the three walls was calculated, because this coincides with the overall heat transfer that occurs through the external vertical envelope.

The conductive flux (C) was calculated according to the Fourier's law of thermal conduction by:

$$C = \Delta T \cdot R_t^{-1}. \left[\mathrm{W\ m^{-2}}\right], \tag{1}$$

where ΔT [K] is the temperature difference between the wall external and the internal surface and R_t [K W^{-1} m^2] is the overall wall thermal resistance.

2.3.2 Long-wave infrared radiative flux

In wintertime, the thermal barrier effect provided by the GL can be particularly beneficial. The long-wave infrared (LWIR) radiative flux plays an important role in the thermal barrier effect. To assess this the LWIR energy balance at the external surface of the BW and of the CW with *Rhyncospermum jasminoides* was performed for a representative winter week.

According to Convertino et al. [16], LWIR radiative energy balance (RB) at the external surface of the BW (RB_{bw}) and of the CW (RB_{cw}) was calculated by:

$$RB_{bw} = \varepsilon_{ws}\left(R_{sky} + R_g\right) - R_{e,bw} \cdot \left[\mathrm{W\ m^{-2}}\right], \tag{2}$$

$$RB_{cw} = \varepsilon_{ws} R_{i,gl} - R_{e,cw} \cdot \left[\text{W m}^{-2}\right], \tag{3}$$

where ε_{ws} is the infrared emissivity coefficient of the wall external surface, R_{sky}, R_g, $R_{e,bw}$, $R_{i,gl}$ and $R_{e,cw}$ [W m^{-2}] are the LWIR radiative fluxes emitted by the sky, the ground, the external surface of the BW, the inner side of the GL and the external surface of the CW, respectively.

3 RESULTS AND DISCUSSION

The monthly climatic data recorded during the winter field test are shown in Fig. 2.

The lowest air temperature (–0.3°C) was recorded in January 2015, the highest (22.6 °C) in February 2016. The highest values of monthly cumulative solar radiation on a horizontal (238 MJ m^{-2}) and vertical (338 MJ m^{-2}) plane were found in February 2016 and January 2015, respectively. The lowest values of monthly cumulative solar radiation on a horizontal (177 MJ m^{-2}) and vertical (254 MJ m^{-2}) plane were recorded in January 2016 and February 2015.

The influence of GFs in winter was analysed by considering the heating effect these provided. This was defined as the positive difference between the external surface temperature of the CW and of the BW. In the case of a negative difference, a cooling effect was recorded. Table 1 shows the maximum and the average values recorded during the whole test period.

Heating was recorded at night-time due to the thermal barrier effect, while cooling at daytime due to the solar radiation shading effect provided by the GF.

3.1 Statistical analysis

Statistical analyses highlighted the relationships between the heating effect recorded on the two GFs and the climatic parameters ($T_{ext,a}$, $RH_{ext,a}$ and w) during night-time. ANOVA revealed significant differences at $P < 0.001$. The results showed that among the considered climatic parameters ($T_{ext,a}$, w and $RH_{ext,a}$) and their interaction, $T_{ext,a}$ caused the highest variability in the two GFs (Table 2).

The magnitude of the heating effect for the two GFs depends on the variation of the climatic parameters as highlighted by the Tukey–Kramer's test (Table 3). As $T_{ext,a}$ decreased,

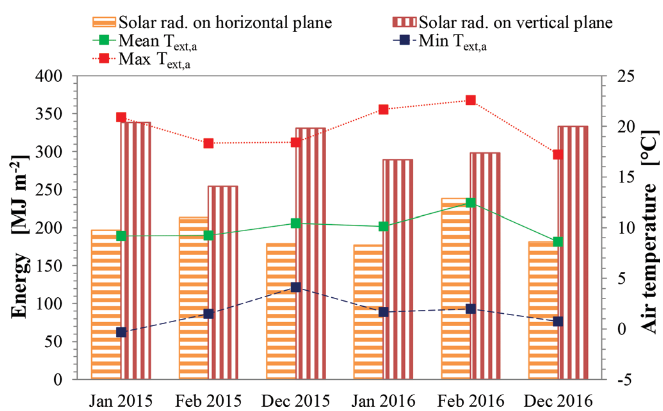

Figure 2: Monthly values of cumulative solar radiation on horizontal and vertical plane (primary axis) and of mean, minimum and maximum external air temperature ($T_{ext,a}$) (secondary axis) in January, February and December, 2015 and 2016.

Table 1: Heating and cooling effect recorded at the experimental green façades.

Green façade type	Heating effect [°C]		Cooling effect [°C]	
	Maximum	Average	Maximum	Average
Rhyncospermum jasminoides	3.5	1.1	8.3	2.1
Pandorea jasminoides	3.5	1.2	7.7	2.2

Table 2: Influence of the climatic parameters on the surface heating ($\overline{\Delta T_{ws}}$) at night-time of the wall behind the *Rhyncospermum jasminoides* (*R.j.*) and the *Pandorea jasminoides* (*P.j.*), ANOVA analysis.

Source[1]	*df*		MS		*F*		*P*	
Main effects	*R. j.*	*P. j.*	*R. j.*	*P. j.*	*R. j.*	*P. j.*	*R. j.*	*P. j.*
$T_{ext,a}$	7	7	103.96	59.89	398.41	218.84	***	***
w	5	5	23.65	14.67	90.65	53.60	***	***
$RH_{ext,a}$	6	6	2.30	8.38	8.82	30.63	***	***
Interaction								
$T_{ext,a}*w$	35	35	4.42	3.82	16.95	13.97	***	***
$T_{ext,a}*RH_{ext,a}$	37	37	2.87	3.84	10.99	14.02	***	***
$w*RH_{ext,a}$	28	28	1.01	1.19	3.88	4.34	***	***
$T_{ext,a}*w*RH_{ext,a}$	131	131	0.82	0.98	3.16	3.59	***	***
Error	10722	10640	0.26	0.27				

[1] $T_{ext,a}$: external air temperature; w: wind speed; $RH_{ext,a}$: external air relative humidity.
***$P < 0.001$

the heating effect increased. A different behaviour was observed regarding the wind speed. A threshold value equal to 3 m s^{-1} was found for both the GFs. As w increased, the heating effect increased till w reached 3 m s^{-1}. Starting from this value, as w increased, the heating showed a decreasing trend. Concerning the influence of $RH_{ext,a}$, a weaker dependence was found. In the case of the CW with *Rhyncospermum jasminoides,* when $RH_{ext,a}$ increased up to 60%, the heating effect increased; for $RH_{ext,a}$ values higher than 70%, the heating performance decreased. In the case of the CW with *Pandorea jasminoides*, the heating effect increased up to $RH_{ext,a}$ values lower than 80%, then it decreased.

3.2 Overall heat transfer

The overall heat transfer that occurs through the external vertical envelope was evaluated by eqn (1). Values in Figs. 3–4 refer to periods of 3 days for each winter month in 2015 and 2016.

Positive values stand for energy gained by the indoor air, while negative ones for energy released towards the outdoor environment. The flux oscillation amplitude was in general lower for the GFs (Fig. 3). The difference became clearer in 2016, as a probable consequence of the plant's growth. The fluxes through the CWs were less sensitive to the change of the external climatic conditions throughout the day.

Table 3: Mean surface temperature rise ($\overline{\Delta T}_{ws}$) behind the *Rhyncospermum jasminoides* (*R.j.*) and the *Pandorea jasminoides* (*P.j.*) at night-time, as related to external air temperature, wind speed and air relative humidity intervals, Tukey–Kramer's test.

External air temperature			Wind speed			Air relative humidity		
$T_{ext,a}$ [°C]	$\overline{\Delta T}_{ws}$ [°C]		w [m s^{-1}]	$\overline{\Delta T}_{ws}$ [°C]		$RH_{ext,a}$ [%]	$\overline{\Delta T}_{ws}$ [°C]	
	R. j.	*P. j.*		*R. j.*	*P. j.*		*R. j.*	*P. j.*
<4	1.62^{a}	1.63^{a}	<2	1.02^{c}	1.18^{c}	<40	0.98^{a}	0.90^{c}
[4; 6[	1.48^{b}	1.45^{b}	[2; 3[	1.33^{a}	1.36^{a}	[40; 50[	1.15^{a}	1.08^{c}
[6; 8[	1.34^{c}	1.35^{c}	[3; 4[	1.22^{b}	1.25^{b}	[50; 60[	1.27^{a}	1.21^{bc}
[8; 10[	1.10^{d}	1.20^{d}	[4; 5[	0.99^{cd}	1.01^{d}	[60; 70[	1.16^{a}	1.28^{b}
[10; 12[	0.88^{e}	1.05^{e}	[5; 6[	0.90^{de}	0.95^{de}	[70; 80[	1.25^{a}	1.39^{a}
[12; 14[	0.87^{ef}	0.95^{e}	≥6	0.88^{e}	0.87^{e}	[80; 90[	1.20^{a}	1.28^{b}
[14; 16[	0.84^{ef}	0.94^{e}				≥90	1.14^{a}	1.19^{c}
≥16	0.79^{f}	0.91^{e}						

$\overline{\Delta T}_{ws} = T_{e,cw} - T_{e,bw}$: mean temperature rise of the wall external surface.
Mean values of temperature in a column with a different superscript letter statistically differ at $P < 0.05$ using Tukey–Kramer's test.

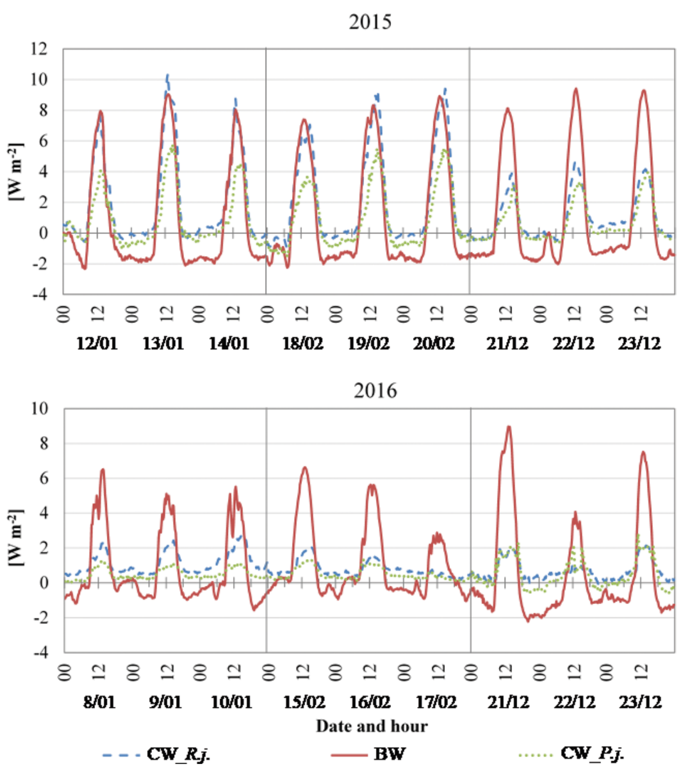

Figure 3: Overall energy transfer through the bare wall (BW) and the walls covered with *Rhyncospermum jasminoides* (CW_*R.j.*) and *Pandorea jasminoides* (CW_*P.j.*).

The difference of the thermal behaviour between daytime and night-time was evaluated, setting daytime when solar radiation was greater than zero.

Figure 4 shows the cumulative overall energy transfer for each 3-day period. In general, the BW gained more energy at daytime, while it always lost more energy at night-time.

In winter 2015, the CW with *Rhyncospermum jasminoides* gained on average 15% less energy compared to the BW at daytime, but recorded energy gains also at night-time, when the BW lost energy (Table 4). In wintertime 2016, the differences were greater: the CW with *Rhyncospermum jasminoides* gained 60% less energy at daytime compared to the BW. At night, the CW gained only 28% less energy than at daytime (Table 4).

In winter 2015, the incoming energy for the CW with *Pandorea jasminoides* was on average 52% lower than that for the BW during daytime, while the outgoing energy was 83% lower at night-time (Table 4). In 2016, at daytime the CW with *Pandorea jasminoides* gained on average 70% less energy than the BW but gained energy also at night (Table 4).

3.3 Long-wave radiative energy flux

The analysis of the LWIR energy exchange was carried out to evaluate its contribution to the thermal barrier effect provided by the GF.

Data gathered on the GF prototype recorded the presence of the thermal barrier effect provided by the GL (Fig. 5, Table 5).

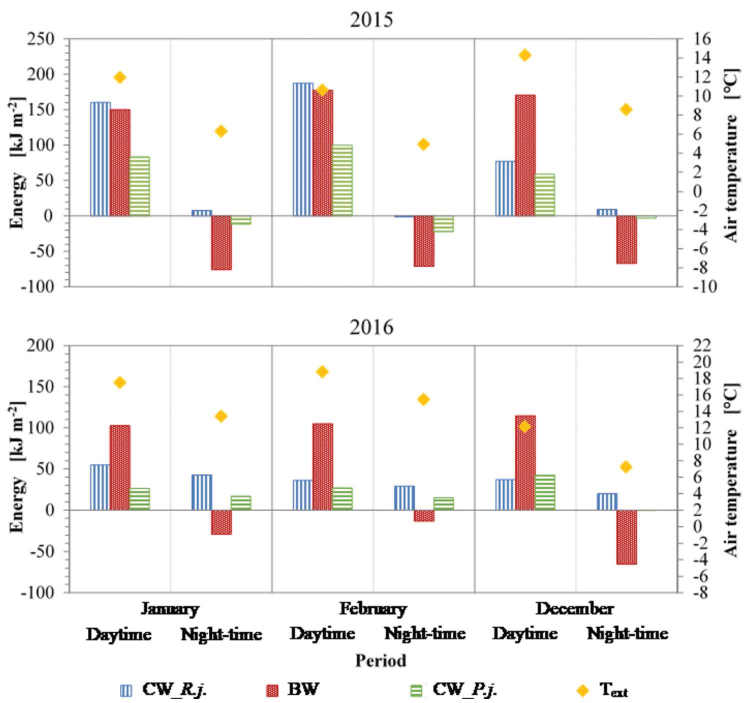

Figure 4: Overall cumulative energy transfer through the bare wall (BW) and the walls covered with *Rhyncospermum jasminoides* (CW_*R.j.*) and *Pandorea jasminoides* (CW_*P.j.*) (primary axis); average daytime and night-time external air temperature ($T_{ext,a}$) (secondary axis).

Table 4: Mean daytime and night-time cumulative overall energy transfer through the bare wall (BW) and the walls covered with *Rhyncospermum jasminoides* (CW_*R.j.*) and *Pandorea jasminoides* (CW_*P.j.*), wintertime 2015 and 2016.

Year	Period	Overall energy transfer [kJ m^{-2}]		
		CW_*R. j.*	BW	CW_*P. j.*
2015	Daytime	+141.51	+165.86	+80.44
	Night-time	+5.20	−71.36	−12.30
2016	Daytime	+42.77	+107.32	+31.81
	Night-time	+30.64	−35.81	+10.62

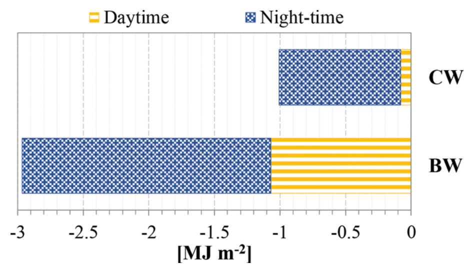

Figure 5: LWIR energy budget at the BW and the CW with *Rhyncospermum jasminoides*: average daytime and night-time values calculated over a winter week.

Table 5: LWIR energy budget on the external surface of the BW and of the CW with *Rhyncospermum jasminoides*; daytime, night-time and all-day average values, calculated over a winter week.

Wall type	Long-wave radiative flux [MJ m^{-2}]		
	Daytime	Night-time	All-day
Bare wall	−1.07	−1.89	−2.96
Covered wall	−0.08	−0.93	−1.01

Throughout the day, the CW lost on average 66% less LWIR energy than the CW. At night-time, the energy losses for the BW were 51% higher than for the CW, this percentage was 93% at daytime.

4 CONCLUSIONS

The wintertime heating effect provided by GFs under Mediterranean climatic conditions was evaluated. Experimental data gathered in winter 2015 and 2016 at the University of Bari (Bari, Italy) were analysed. Data referred to two evergreen GFs and to a BW, used as control.

A night-time heating effect, given by the higher temperature of the external CW surface, was recorded. The statistical analysis recorded the dependence of the heating effect on the climatic parameters such as external air temperature and relative humidity, and wind speed.

External air temperature was the most influencing factor: as it decreased, the heating effect increased. A certain sensibility was found concerning the wind speed, while a weak relationship was recorded for the air relative humidity.

The energy analysis pointed out the advantages provided by the GFs in terms of reduction of conductive and long-wave radiative energy losses at night-time. The green layer allows to keep energy fluxes more constant throughout the day, avoiding peaks of energy gains and losses and acting as a thermal barrier. On the other hand, the GFs reduced the gain of solar radiation during daytime.

The findings of this study represent a contribution to the wintertime evaluation of the performance of GFs over extended time periods. These can help to find out the best site for green façades installation, according to the climatic conditions.

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Notation list.

BW	Bare wall	VGS	Vertical greenery system
C	Conductive energy transfer [W m^{-2}]	w	Wind speed [m s^{-1}]
CW	Covered wall		
GF	Green façade	ΔT	Temperature difference [K]
GL	Green layer		
LW	Living wall	ε_{ws}	Wall surface LWIR emissivity
LWIR	Long-wave infrared	Subscripts	
R	LWIR radiative flux [W m^{-2}]	bw	Bare wall
RB	LWIR radiative balance [W m^{-2}]	cw	Covered wall
RH	Relative humidity [%]	e,bw	External surface of the bare wall
R_t	Wall thermal resistance [K W^{-1} m^2]	e,cw	External surface of the covered wall
T	Temperature [°C]	ext,a	External air
UGI	Urban green infrastructure	g	Ground
UHI	Urban heat island	i,gl	Inner side of the green layer

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