Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green facades

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Abstract

During the last decade, vertical greenery systems are increasing their presence in building designs, providing several urban ecosystem services. One of them is the potential to provide energy savings in buildings, which develops an important role, however, data about its performance during winter periods is still scarce. Therefore, the main objective of this paper is to compare at real scale the thermal performance of two different vertical greenery systems implemented in experimental houses-like cubicles for both cooling and heating periods. A double-skin green facade has been installed in the first cubicle that uses deciduous creeper plants, while the second one is designed with green walls made with evergreen species. Finally, a third identical cubicle without any green coverage is used as reference. Two different types of experiments have been carried out to test the performance of the house like-cubicles. One consists of controlling the internal ambient temperature providing heating or cooling to maintain the desired comfort conditions. On the other hand, to study the thermal response of the construction system, the heating, ventilation and air conditioning system was disconnected and the cubicles were tested under free floating condition. First results showed a high potential for energy savings during cooling season for green wall (58.9 %) and double-skin green facade (33.8 %) in comparison to the reference system. On the other hand, for heating periods no extra energy consumption was observed for evergreen system.

Keywords: Vertical greenery systems; Green wall; Green facade; Energy savings; Green infrastructure; Ecosystem services.

1. Introduction

In recent years, new design trends are being applied in architecture and construction fields so that environmental and social criteria are considered at the same level of aesthetics, economic and functional ones.

These contemporary design criteria provide a new social conception of the building sector. Moreover, they also enhance the quality of the next generation of buildings by introducing environmental concepts that consider the whole life of the materials, energy and water consumed throughout the construction, operational and end of life processes of a building [1].

Within this context, the concept of *Urban Green Infrastructure* has been defined as a set of man-made elements which provides multiple ecosystem services at building and urban scales. Among these functions, building energy saving as well as the reduction of urban heat island effect are stand out. Some of the most innovative and interesting solutions for this purpose are green roofs (GR) and vertical greenery systems (VGS) for buildings [2]. From these two construction typologies, GR and VGS, the second ones have possibly higher potential for improvement [3].

Recent studies about the use of VGS highlight that there are four key factors that influence their operation as passive system for energy savings in buildings [4]:

- First, the sort of construction system used to place plants on the building facades (classification of VGS). Regarding to the classification of these systems it is important to take into consideration the great differences between construction systems, especially between green walls (GW) and green facades (GF) which could influence on the final building thermal behaviour. This is the reason why it is necessary to provide data referring to each system and to avoid the data comparison from different systems.

- Second, the climatic influence, not only on the thermal behaviour of the building but also on the choice of plant species and how this climatic influences their growth.
- Third, the type of plant species used (deciduous or evergreen, shrubs or climbing plants, etc.).
- Finally, the last key factor is related to the various mechanisms that make these systems act as passive tools for energy savings in buildings such as shadow, insulation, evapotranspiration and wind barrier effects.

To organize and summarize all the key factors found in the literature that influence VGS when are applied as passive energy savings systems, Table 1, Table 2 and Table 3, are shown. A total of 23 studies were found, nine related to traditional GF, nine for double-skin GF and five for GW.

From this overview, it should be highlighted the difficulty to establish a proper comparison between studies, when the construction system, the climate, the plants species used, and other parameters (orientation, thickness foliage, etc.) are considered.
In addition, a comparison between studies is difficult since they often use different construction systems and materials.
Despite these drawbacks, if the reductions on the external surface temperatures of the building wall are considered, an approximation about the potential of these systems as passive systems for energy savings, basically through the shadow effect could be established (last column on Table 1, Table 2 and Table 3).

As general assessment, significant reductions on the surface exterior temperature of the building wall can be seen, although there is big variability in the obtained results, ranging from 1 ºC to 31.9 ºC. Moreover, the most influential parameters are the foliage thickness and the facade orientation (especially South and West). However, due to the specific testing conditions of previous studies, the influence of each parameter from an overall perspective cannot be determined.

Regarding to the operation, VGS act basically through four mechanisms; the shadow produced by the vegetation, the insulation provided by vegetation and substrate, the evaporative cooling through evapotranspiration, and, finally, the barrier effect to wind

[5]. From the analysis of previous studies it is verified that the shadow effect has the highest impact over the reduction of the building wall temperature and, consequently, over the energy consumption [4].

In some of these studies, energy savings were indirectly calculated based on reductions of internal temperatures or energy flows through the building wall by considering the thermal properties of the materials, but in none of them a direct measurement of the energy savings provided by green systems was found. The direct measurement of the energy savings allows to quantify objectively the ecosystem service supplied by these systems in a way that allows the subsequent economic quantification thereof. Obtaining this data from different systems and under different climates would allow a comparison between them and would help architects and engineers to make more appropriate decisions in the design phase of buildings. In addition, despite the big interest in this topic, only one study relating to the contribution to energy savings due to the facade orientation was found [22].

Besides, there is a lack of studies and experimental data at real scale concerning the thermal performance of VGS in winter. Specially for living walls, in which the structural support implies, in several cases, an opaque double skin, and for GF in the case of using perennial climbing plants (e.g. ivy species).

The authors of this paper previously demonstrated the ability of these systems to improve the thermal performance of buildings specially through the interception of solar irradiance, reaching shadow factors equivalent to those provided by artificial barriers traditionally used in buildings, such as slats, awnings, etc. [4,5,26]. Due to the positive results of these previous studies, the experimental facilities were technically improved implementing new temperature sensors on all facades with the objective to quantify accurately the energy savings provided by the two main typologies of VGS (GF and GW) during both cooling and heating periods. The study includes the measurement of the accumulated energy consumption for heating and cooling experiments separately. In addition, another goal was to observe and collect information about the influence of the thermal performance by facade orientation for the two studied VGS.

Table 1. Most significant previous studies on the use of VGS as passive tool for energy savings in buildings. Traditional green facades

Authors	Publication year	Location		Köppen classification [6]		Period of study	Plant species	Orientation	Foliage thickness (cm)	External wall surface temperature reduction (ºC)
Hoyano [7]	1988	Japan	Tokyo	Cfa	warm temperate; fully humid; hot summer	Summer	*Parthenocissus tricuspidata*	West	–	13
Köhler [8]	2008	Germany	Berlin	Cfb	warm temperate; fully humid; warm summer	Summer/Winter	*Parthenocissus tricuspidata*	–	–	3 (summer);3 (winter)
Eumorfopoulou and Kontoleon [9]	2009	Greece	Thessaloniki	Cfb	warm temperate; fully humid; warm summer	Summer	*Parthenocissus tricuspidata*	East	25	5.7
Sternberg et al. [10]	2011	England	Byland Abbey, Ramsey, Oxford, Nailsea, Dover	Cfb	warm temperate; fully humid; warm summer	All year	*Hereda helix*	West-South	10 to 45	1.7-9.5 (summer)
Perini et al. [11]	2011	Netherlands	Delft	Cfb	warm temperate; fully humid; warm summer	Autumn	*Hereda helix*	North-West	20	1.2
Cameron et al. [12]	2014	UK	Reading	Cfb	warm temperate; fully humid; warm summer	Summer	*Hereda Helix, Stachys byzantina*	North, South	–	7 - 7.3
Bolton et al. [13]	2014	UK	Manchester	Cfb	warm temperate; fully humid; warm summer	Winter	*Hereda helix*	North	–	+ 0.5 (winter)
Susurova et al. [14]	2014	USA	Chicago	Dfa	snow; fully humid; hot summer	Summer	*Parthenocissus tricuspidata*	East, South, West and North	20	12.6
Haggag et al. [15]	2014	United Arab Emirates	Al Ain City	BWh	arid; desert; hot arid	Summer	–	–		6

Table 2. Most significant previous studies on the use of VGS as passive tool for energy savings in buildings. Double-skin green facades

Authors	Publication year	Country	Location	Köppen classification [6]		Period of study	Plant species	Orientation	Foliage thickness (cm) or (%)	Air layer (cm)	External wall surface temperature reduction (ºC)
Hoyano [7]	1988	Japan	Kyushu	Cfa	warm temperate; fully humid; hot summer	Summer	Dishcloth gourd	South-West	55 %	–	1 to 3
Koyama et al. [16]	2013	Japan	Chikusa	Cfa	warm temperate; fully humid; hot summer	Summer	Bitter melon, Morning glory, Sword bean, Kudzu, Apios	South	54-52-29-52-15 %	–	4.1 - 11.3 - 7.9 - 6.6 - 3.7
Wolter et al. [17]	2009	Germany	Pillnitz, Dresden	Cfb	warm temperate; fully humid; warm summer	–	*Hereda helix* cv. woerner	North, South, West, East	–	–	–
Ip et al. [18]	2010	England	Brighton	Cfb	warm temperate; fully humid; warm summer	–	*Parthenocissus quinquefolia*	South-West	–	–	–
Perini et al. [11]	2011	Netherlands	Rotterdam	Cfb	warm temperate; fully humid; warm summer	Autumn	*Hereda helix, Vitis, Clematis, Jasminum, Pyracantha*	–	10 cm	20	2.7
Suklje et al. [19]	2013	Slovenia?	Ljubljana?	Cfa / Cfb	warm temperate; fully humid; hot / warm summer	Summer	*Phaseolus vulgaris* "Anellino verde"	–	–	–	4
Pérez et al. [5]	2011	Spain	Lleida	Csa	warm temperate; summer dry; hot summer	All year	*Wisteria sinensis*	South-East	20 cm	50-70	15.18 (summer)
Pérez et al. [20]	2011	Spain	Lleida	Csa	warm temperate; summer dry; hot summer	Summer	*Parthenocissus tricuspidata, Lonicera japonica, Clematis sp, Hereda helix*	South	–	–	–
Wong et al. [21]	2010	Singapore	Singapore	Af	equatorial; fully humid	Winter	Experiment Nº2: climber plants	–	–	–	4.36
Jim [22]	2015	China	Hong Kong	Cwa	Warm temperate; winter dry; hot summer	Summer day (a)Sunny (b)Cloudy (c)Rainy	*Ficus pumila, Campsis grandiflora, Bauhinia corymbosa, Pyrostegia venusta*	East, South, West, North	–	–	(a) 5 (b) 1 to 2 (c) 1 to 2

Table 3. Most significant previous studies on the use of VGS as passive tool for energy savings in buildings. Green walls

Authors	**Publication year**	**Country**	**Location**	**Köppen classification [6]**		**Period of study**	**Plant species**	**Orientation**	**Substrate type / thickness (cm)**	**Foliage thickness (cm)**	**Air layer (cm)**	**External wall surface temperature reduction (ºC)**
Chen et al. [23]	2010	China	Wuhan	Cfa	warm temperate; fully humid; hot summer	Summer	Six different sps	West	Light substrate / 10		Adjustable 3 - 60	20.8
Perini et al. [11]	2011	Netherlands	Benthnizen	Cfb	warm temperate; fully humid; warm summer	Autumn	Evergreen sp	West	Soil / 22	10 cm	4	5
Olivieri et al. [24]	2014	Spain	Colmenar Viejo	Csa	warm temperate; summer dry; hot summer	Summer	Sedum sp	South	8 cm substrate + 7 cm extruded polystyrene	–	None	15.1 - 31.9
Mazzali et al. [25]	2013	Italy	(A) Lonigo (B) Venezia	Cfa	warm temperate; fully humid; hot summer	Summer	Several, shrub, herbaceous and climber species	(A) South-West / (B) South-West	Felt / 1	–	(A) Open 5 / (B) Close 3	Day: (A)12 - 20; (B) 16 / Night: (A) 2 - 3; (B) 6
			(C) Pisa	Csb	warm temperate; summer dry; warm summer	Autumn	Several, shrub, herbaceous and climber species	East	Soil / 5	–	Open 5	Day: 12 / Night: 3
Wong et al. [21]	2010	Singapore	Singapore	Af	equatorial; fully humid	–	N3: *Hemigraphisrepanda*, N6:*Phyllanthus myrtifolius, Tradescantia spathacea* (N1, N4, N5, N7 moses, N8 ????)	–	Several -Soil substrate - Inorganic substrate - Green roof substrate	–	–	Day: 1 to 10.94 / Night 2 to 9 (depending on the system)

2. Materials and methodology

2.1. Climatic conditions

The experimental site is located in Puigverd de Lleida, Catalonia, in the north-east area of Spain at latitude 41ºN under Mediterranean continental climatic conditions defined as Csa (warm temperate; summer dry; hot summer) according to Köppen-Geiger climate classification [6]. The winters are foggy, cold and humid with frosts during some nights and occasionally snowfalls, while the summers are hot and dry. The yearly rainfalls are scarce and are concentrated in spring and autumn seasons ranging from 320 to 500 mm.

2.2. Experimental set-up

Three house-like cubicles with identical walls and roofs construction systems (Figure 1) have been built to carry out the experiments. Their external dimensions are 3 x 3 x 3 m, and can be considered real scale experiments but under controlled conditions as in laboratories. Their foundations are made of in situ reinforced concrete slabs of 3.6 × 3.6 m. Moreover, the roof construction system shows the following layers from inside to outside: 5 cm of extruded polystyrene, coating with plaster, precast concrete beams and ceramic floor arch of 25 cm of thickness, concrete relieved pending formation of 2 %, double asphalt membrane, and a single layer of gravel of 7 cm thickness.

Figure 1. Experimental set-up in Puigverd de Lleida, Spain.

A GW and a double-skin GF system were installed on the East, South and West facades of two identical cubicles oriented to the main cardinal points to compare and measure the thermal behaviour and quantify the passive energy savings potential. In addition, an identical reference cubicle without greenery was used for comparison. Therefore, differences in energy consumption and thermal behaviour between all of them are only attributed to these VGS systems.

The walls evaluated in this study are composed by the following construction systems:

a) Reference. The walls have the following layers from inside to outside: gypsum as internal coating, alveolar brick (30 × 19 and 29 cm thick), and cement mortar as external protection coating. Furthermore, previous experimental studies [27,28] demonstrated that an extra insulation layer is not required due to the thermal performance provided by alveolar bricks.-. The overall thermal transmittance of the walls is 0.784 $W/m^2 \cdot K$ (Figure 2a).
b) Double-skin GF. All the walls have the same construction system than the reference with the exception of a double-skin green facade which was installed as outermost layer on the East, South and West walls (Figure 2b).
c) GW. All the walls have the same construction system than in the reference except having a green wall system as outermost layer on the East, South and West walls (Figure 2c).

Figure 2. Studied cubicles in the experimental set-up in Puigverd de Lleida. From left to right; (a) Reference; (b) Double-skin GF; (c) GW.

A simple metal trellis of 2 mm was installed using screws on East, South and West walls to build the double-skin GF. This system provides an air chamber of 25 cm thickness (Figure 3), according to the gardening and landscaping technical recommendations for VGS [29]. A deciduous plant, Boston Ivy "Parthenocissus tricuspidata", was selected because is ease to climb and presents well adaptation to the specific climatic conditions of the experimental site.

Figure 3. Double-skin GF made with wire mesh and Boston Ivy.

On the other hand, the GW system (Figure 4) is based on square pots (600 x 400 x 80 mm) made of 3 mm recycled polyethylene, that contain 8 cm of coconut fibre as a substrate [30]. Every square module is designed to host 24 small plants, which feed from 4 micro irrigation tubes installed on the top of the module. Moreover, the structural part is based on stainless steel profiles attached to the wall using metallic screws allowing the correct adjustment of the square modules. In addition, its design prevents against the thefts. Finally, two different evergreen shrubs (*Rosmarinus officinalis* and *Helichrysum thianschanicum*) were selected due to its well adaptation to survive in a Mediterranean climate.

Figure 4. GW made with polyethylene modules filled with coconut fibre substrate and native shrubs.

2.3. Instrumentation

A heat pump was installed in each cubicle to provide both cooling and heating. The electrical energy consumption of the heat pump was registered at 5 min interval for each cubicle as well as the parameters listed below:

- Indoor and outdoor surface temperatures of East, West and South walls.
- Indoor ceiling and floor temperatures.
- Indoor ambient temperature and humidity (at a height of 1.5 m).
- Outdoor air temperature at 15 cm (air gap between facade and wall), 30 cm (within the green screen) and 50 cm (in front of the green screen) separated from the East, West and South walls.
- Outdoor ambient temperature and humidity.

- Electrical consumption of the heat pump (Fujitsu Inverter ASHA07LCC; heating capacity 3.00 kW; cooling capacity 2.10 kW).
- Global horizontal solar irradiance.
- Global vertical solar irradiance for East, South and West facades.

Pt-100 DIN B probes (accuracy ± 0.3 ºC) are installed to measure the indoor and outdoor surface temperatures. A Middleton Solar pyranometer SK08 is used to capture the global solar irradiance. On the other hand, electrical network analysers (MK-30-LCD – Class 1) register the electrical energy consumption of the heat pumps. The performance of the installed heat pumps has been fully analysed in Payá et al. [31]. Finally, ELEKTRONIK EE21FT6AA21 (accuracy of ± 2 %) measures the air temperatures and humidity.

2.4. Experiments

The experimental set-up allows conducting controlled temperature and free floating tests. In the controlled temperature experiments, the heat pump is used in automatic function to maintain the internal ambient temperature of the cubicle at a set value during the whole test. The electrical energy consumption of the heating, ventilation and air conditioning system (HVAC) of each cubicle is compared using different thermal set points.

On the other hand, it is interesting to study the thermal performance of the two VGS under free floating conditions, when no HVAC system is used. According to the literature, the main parameter found to calculate and compare the passive energy savings for vegetated greenery systems was the thermal behaviour of external wall surface temperatures [4]. Three different averaged parameters were used to define the dynamic thermal performance of the construction system, detailed as follows:

- The thermal stability coefficient (TSC): ratio between inner and outer thermal amplitudes.
- The reduction of daily maximum wall temperature (ΔT) for both VGS in comparison to the reference.

- The thermal lag (h) between inner and outer wall temperature peaks observed for each facade orientation.

3. Results and discussion

3.1. Cooling period

3.1.1. Energy savings study

Based on ASHRAE standards [32], the comfort range considered for cooling period in the Mediterranean continental climate is between 23 ºC and 26 ºC. Therefore a set point of 24 ºC was used to evaluate the thermal behaviour along this period. Moreover, experiments under controlled temperature at 21 ºC and 18 ºC were carried out to test the system under higher cooling demand conditions.

Table 4 summarizes the electrical energy consumption of the heat pumps of each cubicle, the set point temperature, the duration of the tests, as well as the energy savings of the VGS cubicles in comparison to the reference one during the tests.

Table 4. Total cumulative electrical energy consumption of the heat pumps during cooling experimental period of the three studied cubicles.

Period	Set-point (ºC)	Nº of analysed days	Accumulated energy consumption (kWh)			Average energy savings (%)	
			GW	GF	Reference	GW	GF
June 2015	18	10	24.63	33.99	35.78	31.16	5.01
June 2015	21	11	11.98	16.72	20.98	42.93	20.32
July 2015	24	12	13.04	21.01	31.75	58.94	33.83

Regarding the energy consumption, the GW system showed a big potential to save energy during cooling periods as demonstrated through the performed experiments, where up to 58.9 % energy savings in comparison to the reference during the studied period of July under controlled temperature at 24 ºC inside the cubicle were achieved. Moreover, the double-skin GF system reached significant energy savings, up to 33.8 % for the same period. However, depending on the indoor set point temperature a non-linear cooling performance was observed. This is because the contribution of VGS is directly related to the solar irradiance and the cooling required by the demand, as shown in Table 4.

To better understand the energy savings in both VGS, the hourly energy consumed by each cubicle and the solar irradiance of two consecutive summer days are shown in Figure 5. On one hand, the expected higher energy consumption of the reference cubicle compared to greenery systems is clearly reflected, reaching more than double values during peak hours (from 6 pm to 8 pm) in comparison to the GW. In addition, the delay between the solar irradiation peak (which occurs from 1 pm to 2 pm) and the electrical energy consumption peak is about five hours for all cubicles. This is directly related to the high thermal inertia of the wall construction system, which is based on alveolar bricks [27,28].

On the other hand, after sunset (9 pm), the energy consumption of all cubicles tends to be similar for the next seven hours due to the absence of solar irradiance and, consequently, with no effect of the shadow from VGS. Nevertheless, the heat pump of the reference cubicle still consumes more energy during nights (0 am to 4 am) to remove the heat stored in the walls during daytime while trying to achieve the established internal set point. The lowest differences in energy consumption among the three cubicles were from 4 am to 8 am.

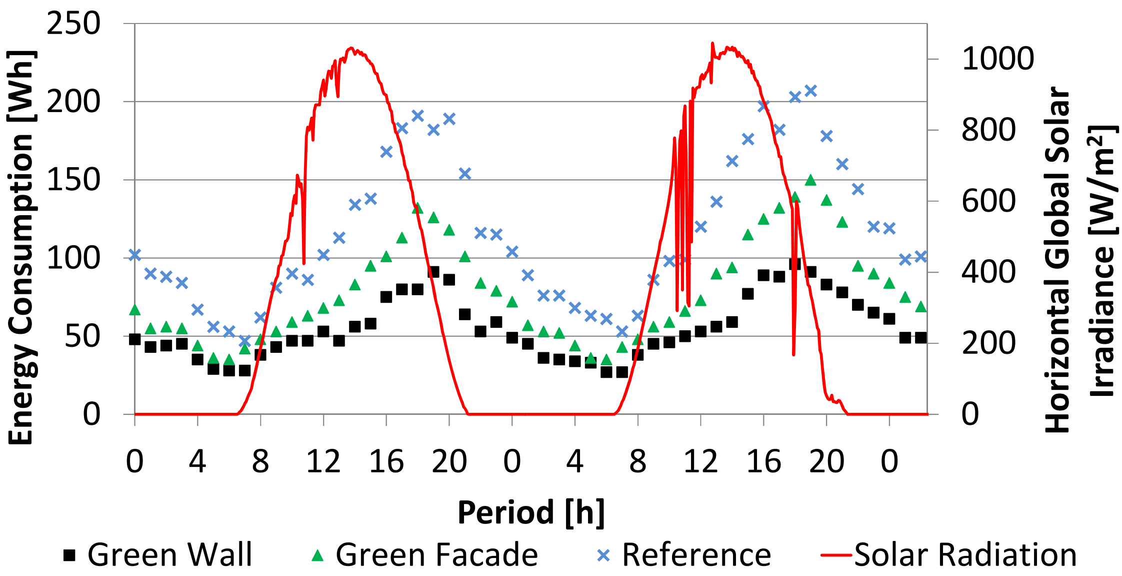

Figure 5. Hourly electrical energy consumption (6 and 7 July 2015). Controlled temperature at 24 ºC (cooling).

The higher energy savings performance of the GW system compared to the GF under the same experimental conditions is attributed to the lower temperatures achieved in the air chamber between the building wall and the greenery system. The recycled polyethylene modules filled of substrate used in the GW system, the dense bushes (Figure 4), the daily irrigation, and the consequent evapotranspiration from substrate and plants, create a heavy protection layer against solar incidence and high summer temperatures in comparison to the single skin made of *Boston Ivy* in GF. Consequently, the temperature peak in the air chamber on the GW system South facade is about 6 ºC cooler, as shown in Figure 6. In addition to the good cooling performance during summer, GW provides an interesting delay of about two hours compared to the outside air temperature, while GF showed the same thermal fluctuations than the outside air. The same thermal performance was seen for East and West facades.

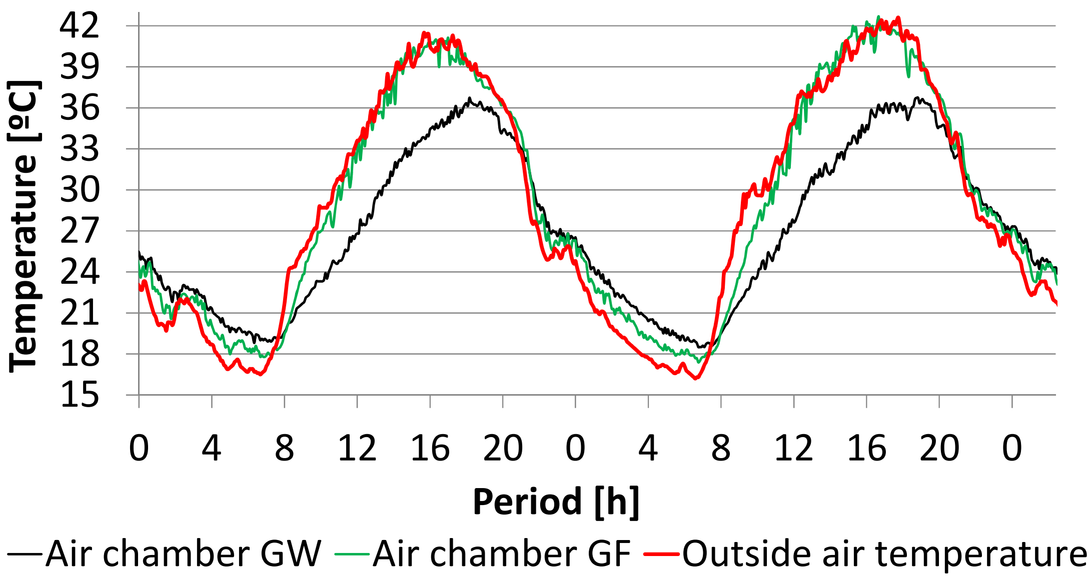

Figure 6. Thermal performance of the southern air chamber for the GW and the GF systems (6 and 7 July 2015). Controlled temperature at 24 ºC.

The energy performance versus the daily average vertical solar irradiation of both GW and GF systems are shown in Figure 7 to confirm the direct relation between them. For twelve consecutive days tested under controlled temperature at 24 ºC, GW showed higher energy savings, ranging from 50.9% to 75.4% and GF showed values between 26% and 47.2%, both of them compared to the energy consumed by the reference system. As the regression equation shows, GW reduces the energy consumption 23.4% every 1000 Wh/m^2 of incident daily vertical solar irradiation, while GF provides a reduction of 19.4%. On the other hand, the energy performance of both VGS versus the outside air temperature have been analysed, showing no correlation between them, and demonstrating that the solar irradiance is the key parameter to determine whether VGS can be effectively used as passive system.

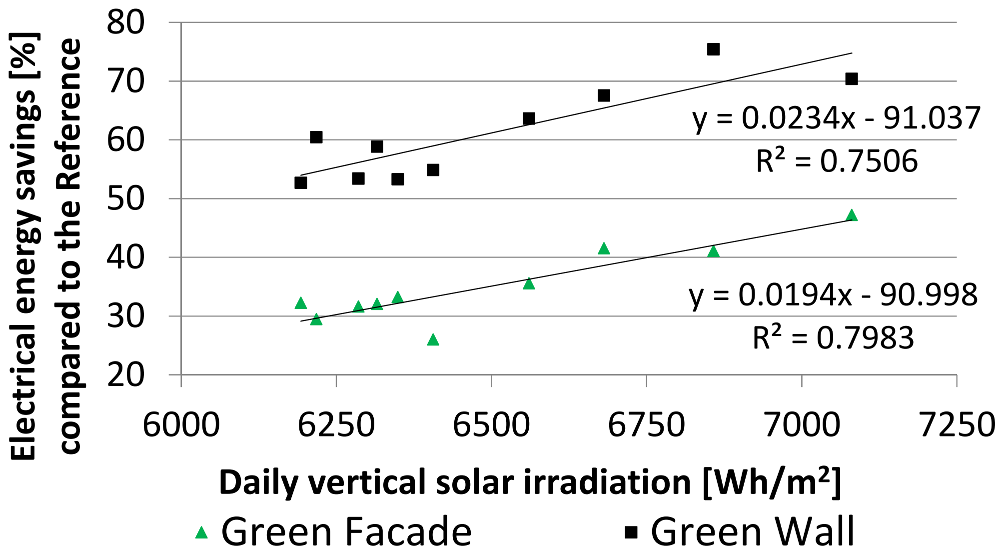

Figure 7. Thermal performance of VGS versus the daily average vertical solar irradiation received by each cubicle during twelve days testing with a set point of 24 ºC.

The results from the summer period showed several similarities with the results obtained by Jim 2015 [22], where the higher solar irradiance, the higher VGS cooling effect. However, due to the location of the study performed by Jim 2015, the vertical solar irradiation was lower in comparison to the horizontal one for each orientation where the effects of shade and insulation were minimized, meanwhile the transpiration effect from vegetation gained relevance in their study.

The obtained results in this study are in good agreement with previous work done by the authors listed in Table 2 and Table 3 for both greenery systems, where GW showed lower energy consumption in comparison to GF. Furthermore, the present study provides experimental data about energy savings, which have a special interest to calculate the economic savings during the operational phase of the building, and allows a better understanding of the shadow effect provided by VGS.

3.1.2. Thermal performance analysis without HVAC systems

The averaged results of the TSC, ΔT and thermal lag, as defined in section 2.4, are calculated for thirteen consecutive days of July 2015 and are presented in Table 5.

Table 5. Thermal stability coefficient (TSC), average of the external wall temperature reduction and thermal lag provided for the three construction systems tested.

Cubicle	TSC		East wall		South wall		West wall	
	Value	Standard deviation	ΔT (ºC)	Thermal lag (h)	ΔT (ºC)	Thermal lag (h)	ΔT (ºC)	Thermal lag (h)
GW	0.037	0.015	17.0	9.29	21.5	9.42	20.1	9.74
GF	0.061	0.018	13.8	9.62	10.7	9.46	13.9	9.21
Reference	0.083	0.018	-	9.91	-	9.58	-	8.66

After the thermal behaviour evaluation according to the orientation, both GW and GF cubicles present significantly lower TSC in comparison to the reference. This reduction in TSC shows clearly the insulation mechanism produced by the GW and GF systems, therefore both require less energy to achieve the desired internal comfort conditions in summer, demonstrating their potential to be used as passive system in building envelopes. Moreover, the standard deviation shows the low dispersion of the TSC values throughout the experiment.

In addition, VGS cubicles provide significant reductions of external wall surface temperatures in all tested orientations (East, South and West) compared to the reference cubicle (Table 5). The highest wall temperature reductions occurred on East and West facades for GF cubicle, while in GW occurred on the South and West orientations. These values are really useful to obtain an approach about the thermal insulation capacity; they can be also compared against other similar studies carried out under different climatic conditions. Similar reductions for GW (Table 3) were obtained by Olivieri et al. [24] in Spanish climate (Csa), and by Mazzali et al. [25] in Italy and Chen et al. [23] in China, both with similar climatic conditions (Cfa). However, only temperature reductions of one facade orientation and one period (summer or autumn) were shown in all of those studies. Therefore, data in relation to the main influencing cardinal direction and different seasons of the year are necessary to obtain a complete picture of the building performance.

Regarding to the double-skin GF system (Table 2), only Pérez et al. [5] obtained similar results for South-East orientations for a whole year while the rest of authors listed in the literature do not mention several properties such as: the foliage thickness [17-22], the thickness of air chamber [7,16-22], the wall surface temperature reduction [17,18,20], the facade orientation [11,19,21], and the period of the study [17,18], to characterize and compare these systems.

On the other hand, in relation to the analysis of the thermal lag, the results demonstrated that the alveolar brick layer is the main responsible of the thermal energy storage capacity of the whole envelope, while GF and GW systems do not provide any significant variation to the thermal inertia of the construction system.

From an overall point of view, the literature reviewed [4] concerning to VGS mentions the orientation used to carry out the experiments, however, the difference on the thermal performance due to the different possible orientations was not analysed. Only, Jim 2015 [22], studied the influence of double-skin GF orientation during one day for three different summer scenarios (sunny, cloudy and rainy days) in the humid-tropical climate (Cwa) of Hong Kong.

3.2. Heating period

3.2.1. Energy savings study

The main objective of the heating experiment is to evaluate whether VGS causes or not extra energy consumption on the building due to the interception of solar gains. Only two previous authors from the literature have provided data on the contribution of these systems in winter, always referring to exterior superficial temperatures of the building facade wall, with contradictory results, -3 ºC and +0.5 ºC respectively, under an ivy traditional GF [8,13].

The experiments for the heating period were studied considering a comfort range from 20 ºC to 24 ºC based on ASHRAE standards [32]. Therefore, in this study a set point of 22 ºC was selected.

Table 6 summarizes all parameters and results obtained in heating experiments: the electrical energy consumption of the heat pumps of each cubicle, the set point temperature, the duration of the tests, and the energy performance of the VGS cubicles in comparison to the reference one.

Table 6. Total cumulative electrical energy consumption of the heat pumps during heating experimental period of the three studied cubicles.

Period	**Set-point (ºC)**	**Nº of analysed days**	**Accumulated energy consumption (kWh)**			**Average energy savings (%)**	
			GW	**GF**	**Reference**	**GW**	**GF**
Dec. 2014	22	17	89.92	93.00	92.66	2.96	-0.36
Jan.-Feb. 2015	22	9	52.43	53.69	54.73	4.20	1.90

As it can be seen in Table 6, the double-skin GF, which uses deciduous creepers plants (Boston Ivy), takes advantage of solar gains during the heating period and allows solar radiation reaching the building facade walls. This effect implies no extra electrical energy consumption during winter period in the GF cubicle for the studied period.

On the other hand, the GW cubicle, which is evergreen and opaque, showed an interesting slight reduction of energy demand for the heating period (Table 6). That fact could be attributed to their night radiative protection (insulation effect) supplied by vertical polyethylene modules filled with substrate. The external surface walls of GW radiate less energy to the sky, while GF and Reference cubicles have a direct wall exposition to the sky.

As it can be verified, according to the obtained results, no major differences in the behaviour of the three cubicles were found during the heating period. Therefore, it could be stated that the incorporation of VGS on the facades of a building by means of deciduous GF or GW do not penalize the thermal behaviour of this building during winter periods.

Even in the case of GW, and given the addition of a new layer on the building envelope, an extra insulation effect is provided to the building, which could be improved in the future with new and better module designs (thickness, type of substrate, type of plants, irrigation regime, etc.).

3.2.2. Thermal performance analysis without HVAC systems

The thermal performance during winter season without HVAC systems was tested from 28 December 2014 to 4 January 2015.

Table 7 shows the thermal response of the external surface wall temperatures by facade orientation to determine the sensitivity of the house like-cubicles when different VGS are applied on East, South and West facades for winter season.

Table 7. Thermal Stability Coefficient (TSC), average of the external wall temperature reduction.

Cubicle	TSC		East wall	South wall	West wall
	Value	Standard deviation	ΔT (ºC)	ΔT (ºC)	ΔT (ºC)
GW	0.063	0.031	4.5	16.5	6.5
GF	0.118	0.026	-0.2	0.7	-0.3
Reference	0.099	0.023	-	-	-

The thermal stability of GF was reduced at similar values of the Reference cubicle during winter period due to the Boston Ivy plant lost her leaves, therefore both cubicles allow the solar gains directly on the walls (daytime) especially on the south facade, increasing the external wall surface temperatures up to 36.4 ºC (Figure 8). However, at the same time, the cubicle also allows the direct contact to the sky and its walls are cooled by radiation during night-time until -8.6 ºC, as shown in Figure 8. On the other hand, the evergreen GW maintain a high thermal stability due to their opaque layer, which provide radiative insulation for the walls during night-time (-2.3 ºC), but reduces solar gains in daytime reaching external wall temperatures up to 5.3 ºC.

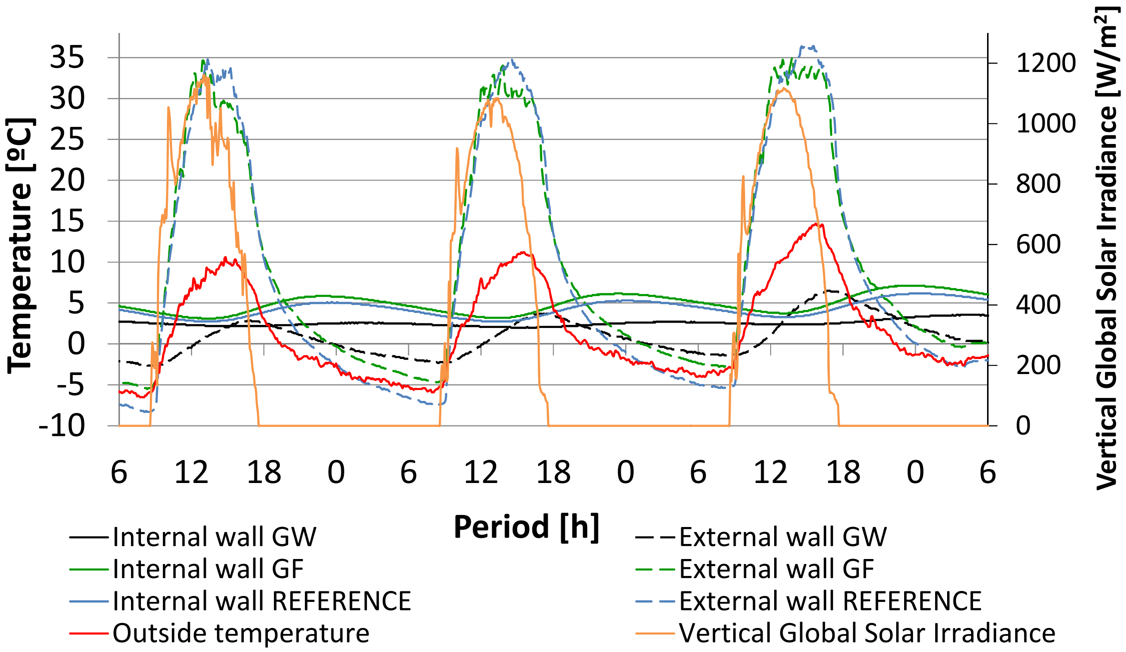

Figure 8. Internal and external south wall temperature evolution for the three studied cubicles without HVAC systems. From 2 to 4 January 2015 (winter).

In relation to the external wall temperatures reduction by facade orientation, the values obtained on the GW south facade (Table 7) highlight that the highest solar irradiance for winter periods is on the South. On the contrary, East and West facades showed lower temperature reductions as they were exposed to less solar radiation.

4. Conclusions

In this paper two different VGS (GW and GF) were evaluated as passive energy savings systems thorough summer and winter seasons of 2014-2015 and compared against a reference system in a real scale set-up under Mediterranean continental climate. In addition, a study of the VGS contribution to these energy savings, by means the thermal assessment of the external surface temperatures of the walls, is performed for the East, South and West orientations.

The overall electrical energy consumption tests confirm the high potential from both VGS to save energy in summer. The GW system provided the highest cooling performance achieving savings of 58.9 %, while the GF presents a reduction of 33.8 %, both of them compared to the reference cubicle with internal comfort conditions at 24 ºC.

In addition, tests carried out under higher demanding conditions (21 ºC and 18 ºC) also showed energy savings for both VGS, but their cooling performance were lower when the set-point became more restrictive.

Moreover, a direct relation between solar irradiation and energy savings was found indicating higher energy savings potential in climates with high solar irradiance. For each kWh of solar irradiation, GW and GF systems reduce the energy consumption by 23.4 % and 19.4 %, respectively.

On the other hand, the GW cubicle also provides energy savings up to 4.2 % during heating periods due to the thermal stability supplied by the polyethylene modules, whereas the GF system, which implements deciduous vegetation, showed similar energy consumption than the reference system.

Concerning the thermal performance by facade orientation in winter, GW registered the highest external wall temperature reductions on the South, achieving 16.5 ºC, whereas in East and West were 4.5 ºC and 6.5 ºC, respectively. That fact highlights the important solar gains through the southern orientation in comparison to the East and West.

In addition to the shadow effect of VGS, there are three more effects that should be studied in depth to quantify the thermal performance of these systems. First, further research should be focused on the growing media that can provide different values of insulation depending on the substrate composition; the second is related to the water irrigation control which is a representative factor for the overall thermal behaviour of the system; and finally, the third is related to the management of the air located in the chamber created between the wall and the GW system. In the literature, there are several authors that mention the use of air gap with different thicknesses (from 3 to 10 cm) in their studies, but only one author considers the air gap closed, therefore more studies could be necessary to address this issues.

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