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Green facade for energy savings in buildings: The influence of leaf area index and facade orientation on the shadow effect

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HIGHLIGHTS

- Leaf area index to measure the shadow potential of a green façade.
- Indirect method to measure LAI is suitable for green facades.
- GF provide comparable shadow factor for all orientations than artificial barriers.
- For a LAI of 3.5–4, 34% of energy savings was measured.
- Energy savings provided by GF are wall orientation dependent.

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ABSTRACT

To "green" building envelopes is currently one of the most promising ways to provide energy savings in buildings and to contribute to the urban heat island effect mitigation. The shadow effect supplied by plants is the most significant parameter for this purpose. One way to characterize the potential shadow effect of greenery is to calculate the facade foliar density by means of the leaf area index (LAI). As LAI is commonly used in horizontal crops, their use in vertical greenery systems (VGS) has generated dispersion and uncertainty in previous studies both in terms of methodologies and results obtained. In addition, a lack of data relating to the influence of the facade orientation in the final contribution of vertical greenery to the energy savings has been observed in previous studies.

This study aims at establishing a common and easy way to measure LAI and to lick it to the energy savings provided by VGS. Moreover, the energy savings achieved as well as the influence of facade orientation on the final thermal behaviour of two different VGS, a double-skin green facade and a green wall, was studied.

From the results, it can be stated that the most simple and quick procedure to measure LAI in order to characterize the foliar density of VGS is the indirect method based on the amount of light transmitted through the green screen. From the experimental tests interesting energy savings were obtained (up to 34% for Boston Ivy pant specie with a LAI of 3.5–4, during summer period under Mediterranean continental climate). Moreover, the dependence on facade orientation was confirmed with representative contribution over the whole energy savings from East and West orientation.

1. Introduction

Nowadays, buildings represent the largest energy-consuming sector in the economy, with over one-third of all energy and half of global electricity consumed there. As a result, they are also responsible for approximately one-third of global carbon emissions. With improvements in economic development and living standards expected to increase as the planet's population grows by 2.5 billion by 2050, energy use in the building sector is also set to rise sharply by 50%, placing additional pressure on the energy system [1].

In most regions of the world, heating and cooling loads represent the largest building-sector energy end-use. The building envelope - the boundary between the conditioned interior of the building and the outdoors - can be significantly improved to reduce the energy needed to heat and cool buildings. Therefore, there is an urgent need to make building envelopes more energy-efficient, as 20–60% of all energy used in buildings is affected by the design and construction of the building envelope [1].

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Among other innovative technologies to improve the thermal performance of building envelopes urban green infrastructure, that is green roofs and all vertical greenery systems (VGS), is standing out as one of the most promising [2]. These innovative and environmental friendly envelope systems not only contribute with thermal improvements to the building [3], but they provide also multiple ecosystem services at city scale, such as urban heat island mitigation [4,5].

This research relates specifically to the thermal performance of vertical greenery systems in buildings. In this regard, it must be taken into account the several strategies to vertically "green" a building because clear differences have been previously described, not only related to the design but also to their thermal performance [6]. A first great differentiation takes place between *green walls* (*living walls*) and *green facades*, requiring the former higher levels of maintenance (intensive) than the second (extensive) [6]. Among green facades, in which climber species are mainly used, the so-called *traditional green facades*, when the building facade material is used by plants as support, can be distinguished from *double-skin green facades*, when a real double skin is created by means of lightweight support structures that allows the vertical development of a plant to happen at some distance from the building facade (Fig. 1). This contemporary adaptation of traditional green facades, based on easy designs, is very promising as far as it is basically extensive, and it implies low investments and interacts only superficially with architecture [7,8]. In the present research, a double-skin green facade has been studied as passive tool for energy savings in buildings.

Referring to the contribution of these VGS to energy savings in buildings, this ecosystem service takes place essentially due to the shadow provided by the plants. Other effects that can contribute, although with minor magnitude, are cooling (evapotranspiration from plants and substrates), insulation (insulation capacity of the different construction system layers: plants, air, substrates, felts, panels, etc.), and the wind barrier effect (modification of the wind influence on the building surfaces due to the presence of plants and support structures) [3,6].

From the previous research about the potential of double-skin facades as passive tool for energy savings in buildings it can be observed that the most interesting parameters to consider in their analysis are the period of study (cooling, heating or both), the species used, the facade orientation, the foliage thickness (or the coverage percentage), and the air gap thickness between the plant layer and the building facade wall. Referring to the contribution to energy savings, generally the reduction on the exterior surface temperature of the building facade wall ranged from 1 °C to 15.18 °C [3].

In particular, in Hoyano [9] the effectiveness of a vine sunscreen for sun shading was found, reaching reductions up to 60% on solar radiation and 1–3 °C air temperature reductions in the studied veranda. Stec [10] conducted a lab experiment in order to evaluate theoretically (simulation) the shading effect by an Ivy layer (*Hereda helix*) instead of the common blinds layer used in a double-skin green facade. The temperature of the cavity air behind the plants layer was significantly lower (20–35%) than behind the blinds layer. Wong et al. [11] concluded from a large experiment under tropical climate that the average wall surface temperature reduction under the double-skin green facade was 4.36 °C, finding maximum reductions during the afternoon. In Ip et al. [12] indoor air temperature reductions of 5.6 °C during the day and 3.5 °C during the Summer nights were obtained by comparing two identical rooms in an office building due to a sun screen placed in a window of an office building. Pérez et al. [13] measured reductions of 5.5 °C under a building wall shadowed areas of a double-skin facade in reference to sunny areas in August, reaching maximum values of 15.2 °C on the South-West facade in September under Mediterranean continental climate. In similar studies, Perini at al. [14] obtained average reductions of 2.7 °C, and Koyama et al. [15] reductions of 3.7–11.3 °C, with coverage between 15% and 54%. Recently Jim [16] obtained reductions of 5 °C on sunny days and 1–2 °C on cloudy days, standing out the importance of facade orientation on the thermal behaviour.

It can be observed that these previous studies highlight, on one hand, the big potential of these systems to intercept solar radiation and to reduce the building wall surface temperatures, and on the other hand, the relation between this shadow effect and the foliage thickness. However, available data are too sparse and no conclusion referring to the influence of foliage thickness on the thermal behaviour can be withdrawn from these studies. In addition, a lack of experimental data referring to total final energy savings provided by these systems can be noted [3].

A simple way to characterize the thermal benefit that a green facade provides at any time during its development can be to measure the relation between the leaf density of the green layer and the shadow effect and, consequently, the energy savings provided.

In this regard, the most used methodology to characterize the leaf mass of a plant or set of plants is the leaf area index (LAI). Traditionally, the concept of LAI has been used in agriculture and ecology to measure the development and yield of crops, to compare among them and to schedule irrigation and amendments during the crop development [17].

Although some previous authors have used the concept of LAI in order characterize the potential of green facades as a passive tool for energy savings, after a literature review, a lack of knowledge

Fig. 1. Traditional green facade (left) versus double-skin green facade.

about LAI concept applied to this purpose has been found. Thus, key issues such as the way to measure LAI in VGS, the relation between LAI and the energy savings provided by the facade are not yet resolved, fact that justifies deeper research in this direction. The following paragraphs summarize the main findings from the scarce previous authors who have applied the concept of LAI to vertical greenery systems.

Wolter et al. (2009) designed an experimental double-skin green facade, made with a steel trellis support and Ivy plants (*Hereda helix*) in order to study the LAI in green facades. According to these authors, in the case of vertical greenery, LAI describes a relation between the leaf area and the square meters of facade instead of the relation between the leaf area and the square meters of floor as usual (e.g. for green roofs application). Moreover, it is necessary to take into account the fact that in a green facade the LAI value changes with the height. Although Wolter's study do not consider the thermal benefits of green facades, as the LAI index has a direct influence on the foliage density, this value can be linked to the thermal behaviour of green systems. The LAI average measured at each exposition at the end of the testing period was between 7 (East) and 8.51 (South). These leaf area indexes lay in between or are even higher than those of conventional facade greenery with *Hereda helix* (2.6–7.7) [18].

Wong et al. (2009) conducted an interesting simulation about the effects of vertical greenery systems on the temperature and energy consumption of buildings. For this purpose, the authors tried to establish a correlation between LAI and the shading ratio (the ratio of the solar radiation beneath the plant and the bare wall) based on measurements carried out in an experimental set-up in which eight different VGS were compared. Although a correlation between these two parameters was found, it cannot be generalized neither considered concluding, because the measurements were few and were done in very different construction systems (some of them were green facades and the other ones were green walls). The general trend was the expected one, i.e. low solar radiation beneath the plant means that the plant shades the wall effectively. To conduct the simulations authors used specific data from plants, both at building level (*Urechites lutea*, *Ophiopogon japonicas* "Kyoto Dwarf" and *Tradescantia spathacea "compacta"*), with corresponding shading coefficients of 0.986 (high), 0.500 (medium) and 0.041 (low), and at city scale (*Nephrolepis exaltata*, Boston fern, with a LAI of 6.76, even though this plant is a fern, not a climbing plant). In this study, the equipment used to measure LAI and the shading coefficient (solar radiation) is described, but not the methodology neither the goodness of the supplied data [19].

In Ip et al. (2010), a coefficient which tries to characterize the shading performance of a climbing plant canopy over its annual growing and wilting cycle was proposed. The study was based on data from an experiment conducted during 2003 and 2004. In that experiment a double-skin green facade, made with modular trellis and Virginia creeper (*Parthenocissus quinquefolia*), was placed in a window of an office building located in Brighton (UK). A very interesting contribution of this study is the effort to characterize the shadow effect of double-skin green facades. With this aim, the leaf solar transmissivity evolution depending on the number of leaf layers was established from up to 2000 measurements under the green facade, in reference to the received radiation in front of the facade. In this experiment, measures for the solar radiation were carried out with the solarimeter in vertical position, fact which, according to the authors, implies the need to make corrections in the calculations in order to consider only the horizontal component of the radiation that is perpendicular to the facade [12].

Susurova et al. (2013) defined a mathematical model to characterize the thermal effects of plants on heat transfer through building facades. Leaf density, characterized by LAI, appears among the various parameters used for the simulation, being one of the most influential in reducing the building facade wall surface temperature. However, in this study LAI was estimated by measuring the area of a single typical leaf and counting the area of ivy in a picture of a traditional green facade under study [20].

Scarpa et al. (2014) proposed a mathematical model for the energy performance of living walls. Again, LAI was an important parameter to consider in the theoretical model. In this study the two values used for LAI were 3 for a living wall with a "vertical garden" made with different species of shrubs and 5 for a living wall that uses grass as vegetation, surprisingly higher than the first one. These values for LAI come from a previous study conducted by the authors, which were obtained by measuring LAI under the shrubs placed in horizontal position, in the nursery [21].

From this literature it can be concluded that LAI is a key parameter to characterize the foliar density and consequently the thermal behaviour of VGS and especially for green facades, due to the great influence on the shadow effect. Nevertheless, there is a lack not only of suitable data of this parameter but also related to the suitable methodology to measure LAI for these purposes. Thus, along these years of studies a common methodology to measure and use LAI for VGS has not been established. In addition, the LAI of the different species used for VGS, the influence of climate in the development of these species and consequently on LAI values, the variations of LAI according to the height, are questions still to be answered. Having real values of LAI for different plants in different climates, and to link these values to energy savings, can be suitable information to face the design necessities during the building project phase.

The present long-term research aims to study the potential of VGS as passive systems for energy savings in buildings, being one of the main focuses to measure the influence of leaf density, by means of the LAI value, on the thermal behaviour of the whole system. Since this leaf density is dependent on the typology of VGS, the type of plant species, as well as its stage of development and the climatic conditions, it is necessary to establish simple and generalizable working methodologies, in order to easily share and compare data from studies conducted around the world.

In a first phase of this research, an existing double-skin green facade located near to Lleida (Spain), under Mediterranean continental climate was yearlong monitored (Fig. 2). The facade consists in a steel modular trellis support and Glycine climber plants (*Wisteria sinensis*). Understanding the light transmission factor of the double green facade as the ratio between the intermediate space illuminance and the exterior illuminance, this value ranged between 0.04 in July to 0.37 in April, during the season with the foliage fully developed. The exterior building wall surface temperature behind a covered area was 5.5 °C lower than in an exposed area. This difference was higher in August and September, reaching maximum values of 15.2 °C on the South-West facade in September [6].

In addition, the transmission capacity of four different plant species well adapted to this climate was determined by means of a simple experimentation [13]. The species chosen were Ivy (*Hereda helix*) and Honeysuckle (*Lonicera japonica*), as perennial plants, and Virginia creeper (*Parthenocissus quinquefolia*) and Clematis (*Clematis sp.*), as deciduous plants. The results of this experiment showed light transmission factor values of 0.15 for Virginia creeper, 0.18 for Honeysuckle, 0.14 for Clematis and 0.20 for Ivy plants. These values are comparable to the best values of the shadow factor that can be obtained by using artificial barriers for the South orientation (Fig. 3).

In order to measure the energy savings associated with this shadow effect, the green facade was moved to an experimental cubicle in which the big capacity of the green facade to intercept solar radiation was confirmed with reductions in outside wall surface temperature up to 14 °C in July in Mediterranean climate [22].

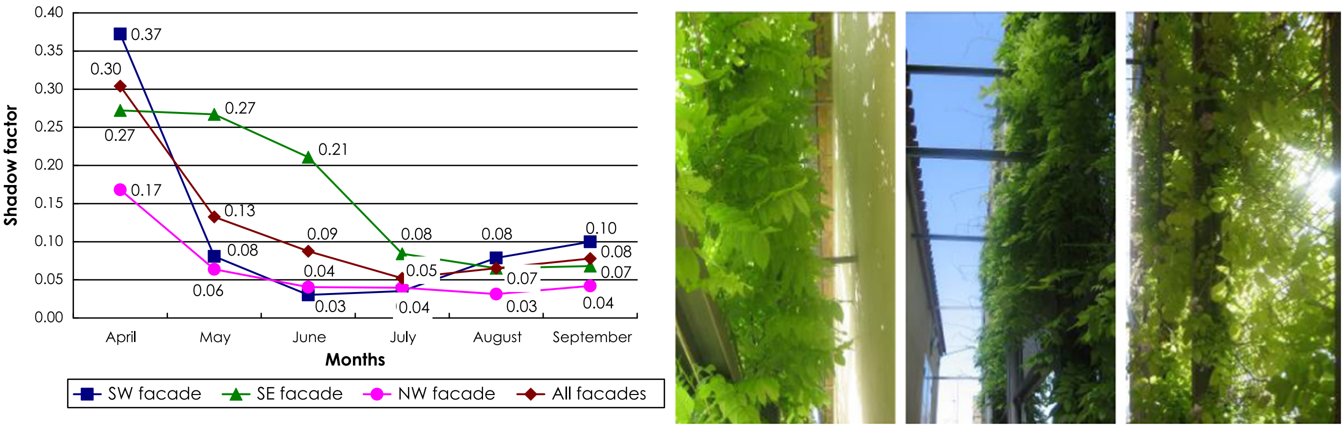


Fig. 2. Shadow factor in a double-skin green facade made with a steel modular trellis support and Glycine climber plants (*Wisteria sinensis*) [6].

Specie	Light transmission factor
Virginia creeper	0.15
Honeysuckle	0.18
Clematis	0.41
Ivy	0.20

Artificial barrier	shadow factor
Cantilever	0.16 – 0.82
Setback	0.17 – 0.82
Opaque awnings	0.02 – 0.43
Translucent awnings	0.22 – 0.63
Horizontal slats	0.26 – 0.49
Vertical slats	0.32 – 0.44

Fig. 3. Shadow capacity of four plant species in reference to the shadow factor of different artificial barriers [13].

Despite this achieved surface temperature reduction, for an indoor set-point of 24 °C, the obtained daily energy consumption reduction in the cubicle was only 1%. This was because at the time of this experimentation the green facade only covered 50% of the South orientation (Fig. 4).

In Pérez [7] the importance of using deciduous species in the regulation of solar gains along the different seasons of the year was considered. The conclusions highlighted the importance of knowing the biological cycle of different species under different climates, because this influences the moment when leaves fall (or grow) and therefore what amount of solar gains could be considered for the thermal balance of the building. This is particularly important in the transition seasons, that are Spring (when the leaves grow) and Autumn (when the leaves fall).

After these positive previous experiences and in view of the potential of the double-skin facade to provide shadow to the building, a new double-skin green facade covering the east, south and west orientations of the experimental cubicle, was built in 2012.

This paper summarizes the main results of the different experiments carried out in this new double-skin green facade addressed to measure the leaf area index (LAI) and to relate it to the shadow effect as well as to the energy savings provided. In addition, the paper attempts to establish a simple and generalizable working methodology for this purpose, so that it can be applied in further research and architectural projects. Finally, it also is an objective the study of how the green facade works depending on the orientation (East, South and West), with the aim to improve the design of these systems in the future.

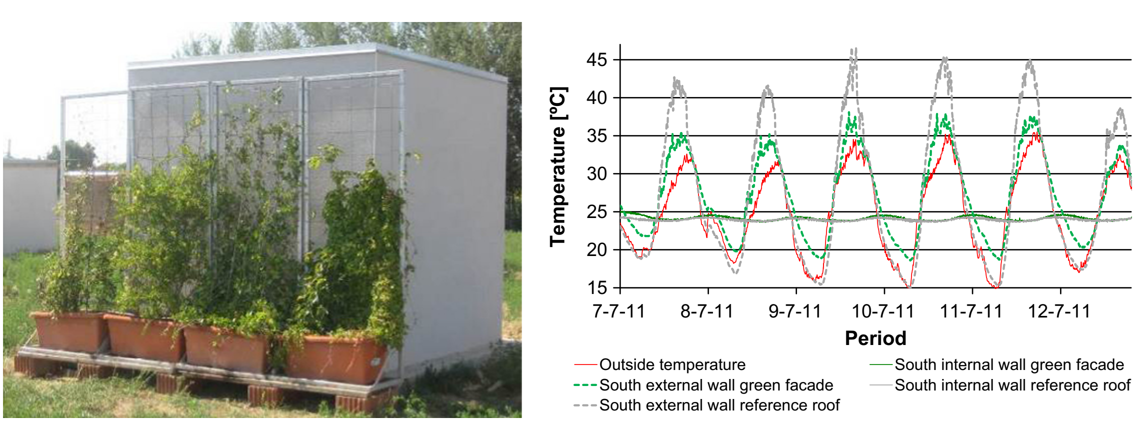


Fig. 4. South internal and external surface temperatures. July 2011. Set-point 24 °C [22].

2. Materials and methods

2.1. Experimental setup

2.1.1. Green facade description

The double-skin facade typology allows complying satisfactorily the requirements listed in the above mentioned VGS classification, and to obtain a good thickness of vegetation with the minimum possible cost of materials and minimum subsequent maintenance (extensive) [7,8].

Therefore, in the experimentation here presented, a simple lightweight steel mesh was anchored, with a set of screws, at 20 cm separated from the building wall creating an intermediate space between the green screen and the building facade wall (Fig. 5).

The double-skin green facade covers East, South and West orientations of the cubicle, being the selected specie Boston Ivy (*Parthenocissus Tricuspidata*), which is a deciduous specie well-adapted to the Mediterranean Continental climate. The selection of the specie was based on the previous experiments [13].

Planting took place in March 2012. A total of 6 plants were planted on each orientation (East, South and West), placed each 0.5 m. In June 2012 a hailstorm hit South and West facades, which had to be replanted again and consequently the plant growth on these orientations was slightly delayed in comparison to East orientation. Plant growth took place during Winter and Spring 2013 and first data were collected during Summer 2013. In order to supply water during the hottest period (Summer), in terms of rain water scarcity, a simple drip irrigation system was installed. The maintenance of this facade is limited to the operations of redirecting the new shoots, to achieve the maximum possible height in the shortest time, an annual pruning, the pesticide treatments in case of diseases, and irrigation during Summer months. Fig. 6 shows the green facade appearance during summer 2015.

2.1.2. Thermal performance and energy savings measurements

This experimentation took place at the experimental pilot plant that *GREA Innovació Concurrent* research group at the *University of Lleida* has in the village of *Puigverd de Lleida* (Spain) in which several studies referring to energy efficiency in buildings have been carried out since 2002 (Fig. 7).

The experimental set-up used in this paper consists of two identical house-like cubicles, with internal dimensions of $2.4 \times 2.4 \times 2.4$ m (Fig. 8). Their bases consist of a mortar base of 3×3 m with crushed stones and reinforcing bars and the walls were composed by the following layers from inside to outside: gypsum as internal coating, alveolar brick ($30 \times 19 \times 29$ cm), and cement mortar as external protection coating. Due to the insulation properties of the alveolar brick, an additional insulation layer is not required in this wall system [23,24]. The overall thermal transmittance of the walls is 0.784 W/m^2 K.

The roof composition is the same in both cubicles and shows the following layers from inside to outside: coating with plaster, precast concrete beams and ceramic floor arch of 25 cm of thickness, 3 cm of polyurethane insulation, concrete relieved pending formation of 2%, double waterproofing membrane, and finished with a single layer of gravel of 7 cm thickness.

The only difference between the two cubicles used in the present research is the use of the double-skin green facade system on the East, South and West facades in one of them.

In order to evaluate the thermal performance of the different studied cubicles, the following data were registered for each cubicle at 5 min intervals:

- Internal and external surface temperatures of East, South and West walls.
- External air temperature at 15 cm (air gap between facade and wall), 30 cm and 50 cm separated from the East, West and South walls.
- Internal ambient temperature and humidity (at a height of 1.5 m).
- Internal ceiling and floor temperatures.
- Electrical consumption of the HVAC system (heat pump Fujitsu Inverter ASHA07LCC; heating capacity 3.00 kW; cooling capacity 2.10 kW).
- Global horizontal solar irradiance.
- External ambient temperature and humidity.

All temperatures were measured using Pt-100 DIN B probes, calibrated with a maximum error of ±0.3 °C. The air temperature and humidity sensors were ELEKTRONIK EE21FT6AA21 with an accuracy of ±2%. The electrical consumption of the HVAC systems was measured using an electrical network analyser (MK-30-LCD). A Middleton solar pyranometer SK08 was used to capture the horizontal global solar radiation. A mobile digital solar power meter HT204T was used to measure the solar radiation.

2.1.3. Climate characterization

Puigverd de Lleida (Spain) has a Mediterranean Continental climate (*Csa, warm temperate - summer dry - hot summer*, according to Köppen classification) [25] which is characterized by cold and foggy winters while summers are hot and dry. Frosts are common during Winter although snow can occasionally fall, averaging 1 or 2 days per year. Precipitations are low, with an annual average 320 mm with a peak in April and May and another peak in September and October. The mean annual temperatures oscillate between 12 and 14 °C, with thermal amplitudes of 17–20 °C.

Fig. 5. Current double-skin facade. Constructive system details and general view.

Fig. 6. Double-skin green facade under study. Summer 2015.

Fig. 7. Experimental set-up in Puigverd de Lleida, Spain.

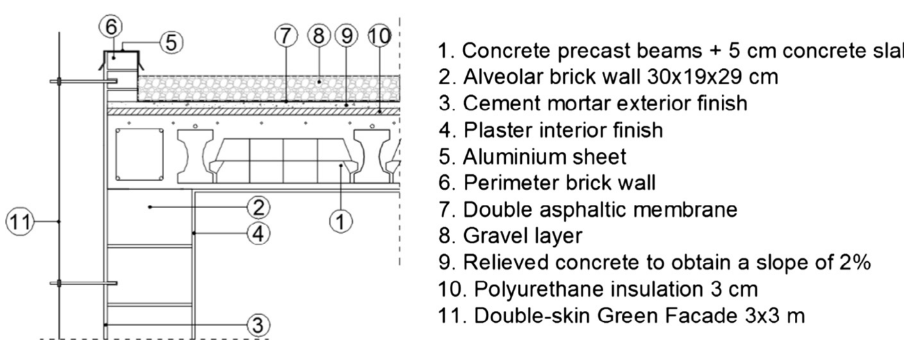


Fig. 8. Constructive section of the cubicles used in the real scale experimental set-up.

2.2. Leaf area index (LAI)

2.2.1. Theoretical approach to LAI measurement

The ability to intercept solar radiation by plants depends on their spatial structure, that is, on the plant canopy three-dimensional geometry. This concept has been extensively studied before and has been applied in the fields of agriculture, with the aim of estimating the growth and yield of crops and therefore the needs of water and nutrients, as well as in the field of forest ecology, in order to estimate the amount of biomass, energy balances and water in ecosystems, etc. [17]. The leaf area index (LAI) is defined as a dimensionless quantity that characterizes canopies structures, becoming a key measure used to understand and compare these plant canopies.

In a parametric approach LAI is established as the one-sided green leaf area per unit ground surface area (LAI = leaf area/ground area, m^2/m^2) in broadleaf canopies [26]. The LAI value depends on the type and the growth phase of the plant (crop), usually ranging from 0 to 10.

The LAI of crops or in a forest ecosystem can be measured according to direct or indirect methodologies. The direct method, which is the most reliable to measure LAI, involves harvesting all the leaves of a plot and measuring the area of each leaf. On the other hand, indirect methods are based on the measurement of parameters directly related to LAI, such as the amount of light transmitted or reflected by the plant canopy [27].

One of the most widely used indirect methods is the photosynthetically active radiation (PAR) inversion technique, based on the estimation of LAI using the amount of light energy transmitted by a plant canopy, so that the more leaf density the more light absorption. This method is based on Beer's law, which is an empirical relation that links absorption of light with the properties of the traversed material. The adaptation of this law, in the case of the canopy capability to intercept solar radiation, is formulated by the following expression [28]:

$$PAR_t = PAR_i^{(-kz)} \quad (1)$$

where PAR_t is transmitted photosynthetically active radiation (PAR) measured near the ground surface, PAR_i is the incident PAR at the top of the canopy, z is the path length of photons through some attenuation medium, which in the case of vegetation canopies accounts for LAI, since leaves are the medium through which photons are attenuated. Finally, k is the canopy extinction coefficient, which describes how much radiation is absorbed by the canopy at a given solar zenith angle and canopy leaf angle distribution.

Taking into account the estimation of LAI, the extinction coefficient could be formulated as:

$$k = \frac{\sqrt{\chi^2 + \tan\theta^2}}{\chi + 1.744(\chi + 1.182)^{-0.733}} \quad (2)$$

where θ is the solar zenith angle and χ is the leaf angle distribution, which describes the projection of leaf area onto a horizontal surface, being $\chi < 1$ for canopies with predominately vertical orientations, $\chi > 1$ for canopies with predominately horizontal orientations, and $\chi = 1$ in the case of a mixture of orientations (spherical leaf distribution).

Known the value of k, LAI is calculated as:

$$LAI = \frac{\left[(1 - \frac{1}{2k})f_b - 1\right]\ln\tau}{A(1 - 0.47f_b)} \quad (3)$$

where A is leaf absorptivity, with a value of 0.9 for most of healthy green foliage (only in extreme cases such as young leaves or highly pubescent or waxy leaves A may deviate from 0.9), f_b is the beam fraction and which is calculated as the ratio between diffuse (scattered in the atmosphere) and beam radiation (direct from the sun), and τ is the ratio of transmitted PAR and incident PAR above the canopy.

The equipment that enables measuring PAR, and LAI following the PAR inversion technique, is the ceptometer. Since the PAR inversion technique is non-destructive, it allows a canopy to be sampled extensively and repeatedly throughout time, and could be applied to a wide variety of canopy samples, it is currently a standard and well-accepted procedure to calculate LAI [28].

The main limitations of the PAR inversion technique are three. First, that it requires measurements of both transmitted PAR (below canopy) and incident PAR (above canopy), under identical light conditions. The second limitation is that in extremely dense canopies PAR absorption may be nearly complete, leaving little transmitted light to be measured at the bottom of a canopy. In this case it is very difficult to observe any variation between extremely high LAI. And finally, it is necessary to collect numerous spatially distributed samples in order to avoid the errors relating to the foliage clumping.

Measurements on overcast days are the simplest for LAI determination because the canopy structure information ($fb = 0$) or solar elevation angle are not needed in such climatic conditions. Moreover, errors associated with incorrectly specifying the leaf angle distribution are most pronounced when sampling under clear sky conditions. In this case Eq. (3) changes to the simplified one:

$$LAI = \frac{-\ln\tau}{A} \quad (4)$$

On which the values of τ and $A = 0.9$ can be replaced, switching to:

$$LAI = \frac{-\ln\left(\frac{PAR_{below}}{PAR_{above}}\right)}{0.9} \quad (5)$$

This simple and quick procedure can also be used to characterize the leaf density of a green facade, so that the resulting value can be related to its ability to intercept solar radiation, and therefore provides a description of its potential as passive tool for energy savings.

2.2.2. LAI measurements description

In order to characterize the leaf density of the double-skin green facade under study and to find a relation between this leaf density and the achieved energy savings due to the shadow effect, different actions were carried out.

First actions took place during Summer 2013. On one hand, the interception of solar radiation provided by plants was measured in different parts of the green facade with the aim to characterize it by orientations as well as by heights. On the other hand, a direct measure of LAI, i.e. destructive, was conducted in the East facade, the most representative plant development at this time of the research. In a second period, during Summer 2015, an indirect measurement of LAI by means of a ceptometer was conducted on the East, South and West facades. In the following sections an accurate description of these actions is provided.

2.2.2.1. Solar radiation 2013. To characterize the interception of solar radiation by the vegetated facade, 15 points were measured in each orientation (East, South and West) under the green screen, close to the building facade wall surface. The acquisition point distribution is divided in three heights (upper, middle and lower) and five measurements in each (Fig. 9) three times a day (10:00 h, 14:00 h and 18:00 h).

These measurements were repeated during two consecutive days under sunshine and clear sky conditions. In order to calculate the shadow factor, the value of the solar radiation outside the green facade was also measured three times (10 h, 14 h and 18 h). Moreover, to confirm similarities between the experimental measurements conducted throughout these days, a statistical analysis using the analysis of variance ANOVA and the Tukey method was carried out.

2.2.2.2. Direct LAI measurement 2013. In order to directly measure the LAI of this green facade using a destructive method, during Summer 2013, once the measurements with the solar meter were finished, all the plant leaves of three square meters on the east facade were removed, a square meter each level (upper level, mid-

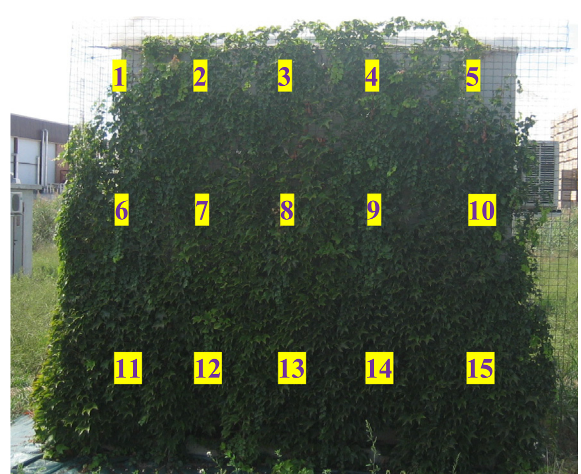


Fig. 9. Location of measurement points for the solar radiation interception characterization.

dle level and lower level, which correspond to the same levels used for the solar meter measurements), according to Fig. 10.

All removed leaves from each square meter were measured individually using a delta-T image analysis system (DIAS) provided with a conveyer belt unit, which allows a quick single measurement of each leave area (Fig. 11). Then, the total leaf area for square meter (upper, middle and lower levels) can be easily calculated.

2.2.2.3. LAI indirect measurement 2015. During Summer 2015, with the green facade in perfect state of development, an indirect measurement of LAI, by using a PAR Sunfleck Ceptometer, was conducted. With the aim of characterizing the LAI by orientation (East, South and West) and for different levels in the facade (upper, middle and lower), a total of 10 PAR measurement repetitions were recorded behind the green screen facade (PAR*below*), in six different points for orientation according to the scheme in Fig. 12. Moreover, the reading of PAR in the outside of the green facade was made in order to obtain the PAR*above* value.

Once, the PAR*below* and the PAR*above* had been measured the LAI could be calculated applying Eq. (5).

3. Results and discussion

3.1. Solar radiation 2013

According to the Spanish Technical Building Code [29], the shadow factor is defined as the fraction of incident radiation on a facade opening which is not blocked by the presence of artificial barriers such as facade setbacks, cantilevers, awnings, slats and others. The shade factor is the ratio between the measured solar radiation behind and in front of a solar barrier. It accounts for the amount of solar radiation that goes through this barrier, and therefore that can reach the building facade wall. Thus, the smaller the solar factor, the greater ability to intercept solar radiation by the solar barrier.

Tables 1–3 show the normalized values for the artificial barriers that are usually used in construction, according to the Spanish Technical Building Code [29]. As it may be seen, the shadow factor is dependent not only on the barrier typology used but also on the building facade orientation.

Table 4 summarizes the results for the calculated shade factor in the different facade orientations (East, South and West) and at different heights (upper, middle and lower levels) on the tested double-skin green facade.

The statistical study conducted to verify whether there were significant differences between the measurements taken during the two repetitions concluded that there were no significant differences between the measurements for all orientations at all hours and for all heights with a confidence level of 95%, allowing using a bigger number of data for shadow factor calculations.

Fig. 11. Delta-T Image Analysis System (DIAS).

The shadow factor obtained for the green facade during daily peaks of solar radiation by orientation (at 10:00 h on the East, at 14:00 h on the South, and at 18:00 h on the West orientation) was equal or lower to the artificial barriers defined in the Spanish Technical Building Code [29] for the same orientations. This fact was also verified on the upper area of the East orientation, where the plants were completely developed.

On the other hand, the upper parts of South and West facades showed higher shadow factor because the plant growth was slightly delayed in comparison to the East orientation, as it was explained in precedent sections. In addition, in the case of the South orientation, the noon high Sun path position through Summer periods and the lower level of vegetation coverage in upper levels of this orientation allowed the sunlight reaching the building facade. The latter statement must be considered in the future design of green facades for South orientations, in order to avoid the influence of solar radiation in Summer periods on the top of the building facade.

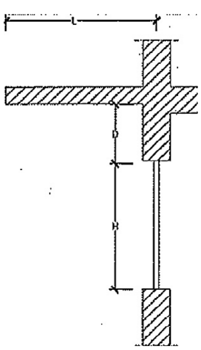
These results confirm and complete those obtained in previous studies [6,13,22] concerning the ability of double-skin facades to provide a dense shadow on the building walls, obtaining comparable shadow factors to those provided by the artificial barriers defined in building regulations. These results enrich the number of possibilities for architects and designers during the building envelope design phase, since green barriers can be added to the traditional artificial solar ones as a suitable way to block solar radiation and to save energy.

The direct consequence of this shadow factor is reflected in the reduction of the external surface building wall temperature, as shown in Fig. 13, with reductions from the first hours of the day that can reach up to 10.1 °C towards 16:00 h, and reductions in the cubicle interior temperatures of around 2.5 °C.

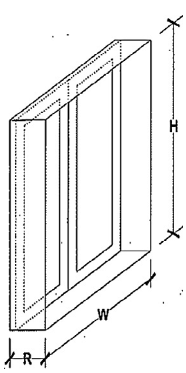
Fig. 10. Direct LAI measurement process during Summer 2013.

Fig. 12. PAR measurements with the Sunfleck PAR Ceptometer during a cloudy day in Summer 2015.

Table 1
Shadow factor for artificial solar barriers. Cantilevers and facade setbacks [29].

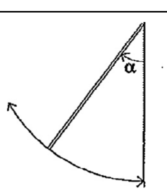


Cantilevers	Facade orientation		$0.2 < L/H \leqslant 0.5$	$0.5 < L/H \leqslant 1$	$1 < L/H \leqslant 2$	$L/H > 2$
	S	$0 < D/H \leqslant 0.2$	0.82	0.50	0.28	0.16
		$0.2 < D/H \leqslant 0.5$	0.87	0.64	0.39	0.22
		$D/H > 0.5$	0.93	0.82	0.60	0.39
	SE/SW	$0 < D/H \leqslant 0.2$	0.90	0.71	0.43	0.16
		$0.2 < D/H \leqslant 0.5$	0.94	0.82	0.60	0.27
		$D/H > 0.5$	0.98	0.93	0.84	0.65
	E/W	$0 < D/H \leqslant 0.2$	0.92	0.77	0.55	0.22
		$0.2 < D/H \leqslant 0.5$	0.96	0.86	0.70	0.43
		$D/H > 0.5$	0.99	0.96	0.89	0.75

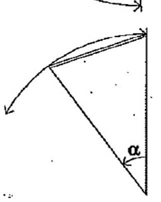


Setbacks	Facade orientation		$0.05 < R/W \leqslant 0.1$	$0.1 < R/W \leqslant 0.2$	$0.2 < R/W \leqslant 0.5$	$R/W > 0.5$
	S	$0.05 < R/H \leqslant 0.1$	0.82	0.74	0.62	0.39
		$0.1 < R/H \leqslant 0.2$	0.76	0.67	0.56	0.35
		$0.2 < R/H \leqslant 0.5$	0.56	0.51	0.39	0.27
		$R/H > 0.5$	0.35	0.32	0.27	0.17
	SE/SW	$0.05 < R/H \leqslant 0.1$	0.86	0.81	0.72	0.51
		$0.1 < R/H \leqslant 0.2$	0.79	0.74	0.66	0.47
		$0.2 < R/H \leqslant 0.5$	0.59	0.56	0.47	0.36
		$R/H > 0.5$	0.38	0.36	0.32	0.23
	E/W	$0.05 < R/H \leqslant 0.1$	0.91	0.87	0.81	0.65
		$0.1 < R/H \leqslant 0.2$	0.86	0.82	0.76	0.61
		$0.2 < R/H \leqslant 0.5$	0.71	0.68	0.61	0.51
		$R/H > 0.5$	0.53	0.51	0.48	0.39

Table 2
Shadow factor for artificial solar barriers. Opaque and translucent awnings [29].

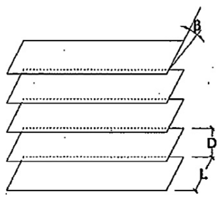


Case A	Opaque textiles $\tau = 0$		Translucent textiles $\tau = 0.2$	
α	SE/S/SW	E/W	SE/S/SW	E/W
30	0.02	0.04	0.22	0.24
45	0.05	0.08	0.25	0.28
60	0.22	0.28	0.42	0.48



Case B	Opaque textiles $\tau = 0$			Translucent textiles $\tau = 0.2$		
α	S	SE/SW	E/W	S	SE/SW	E/W
30	0.43	0.61	0.67	0.63	0.81	0.87
45	0.20	0.30	0.40	0.40	0.50	0.60
60	0.14	0.39	0.28	0.34	0.42	0.48

Table 3
Shadow factor for artificial solar barriers. Slats [29].

Horizontal slats		Inclination angle (β)		
	Orientation	0	30	60
	S	0.49	0.42	0.26
	SE/SW	0.54	0.44	0.26
	E	0.57	0.45	0.27

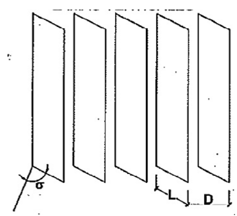
Vertical slats		Inclination angle (σ)						
	Orientation	−60	−45	−30	0	30	45	60
	S	0.37	0.44	0.49	0.53	0.47	0.41	0.32
	SE	0.46	0.53	0.56	0.56	0.47	0.40	0.30
	E	0.39	0.47	0.54	0.63	0.55	0.45	0.32
	W	0.44	0.52	0.58	0.63	0.50	0.41	0.29
	SW	0.38	0.44	0.50	0.56	0.53	0.48	0.38

Table 4
Daily shadow factor evolution by orientation in the studied double-skin facade.

Orientation/height	East			South			West		
Daily time	10:00 h[a]	14:00 h	18:00 h	10:00 h	14:00 h[a]	18:00 h	10:00 h	14:00 h	18:00 h[a]
Upper level	0.19	0.08	0.03	0.12	0.57	0.13	0.08	0.35	0.55
Middle level	0.12	0.05	0.02	0.11	0.26	0.08	0.03	0.28	0.20
Lower level	0.06	0.02	0.01	0.04	0.15	0.05	0.02	0.14	0.06

[a] Maximum solar radiation incidence.

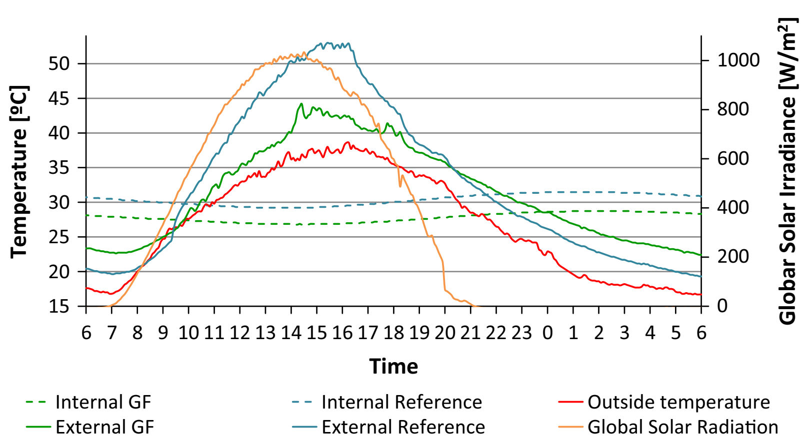


Fig. 13. Daily internal and external South wall surface temperatures on the green facade cubicle under free floating conditions. July 25th 2013 (Summer).

3.2. LAI direct measurement 2013

In the lower level of the facade, as expected, leaves were more developed resulting in a higher LAI for each m^2. Since leaves were much larger the LAI value was close to 4, almost two times higher in comparison to the upper level of the green facade as shown in Table 5.

Thus, for this typology of climber plant, which has a big vertical development, although the number of leaves increased since these are smaller in the upper levels, the value of LAI decreases with height.

These results are in agreement to those obtained by Wolter et al. [18], where the influence of climbing plants height development on the variation of LAI was highlighted. This increment of LAI

Table 5
LAI measurements according to the direct method for the three levels on East orientation of the double-skin green facade.

	Number of leaves	Leaf average surface (cm^2)	Measured leaf area (cm^2)	LAI
Upper level	1387	15.08	20914.64	2.1
Middle level	1224	26.29	32185.04	3.2
Lower level	992	39.60	39283.75	3.9

in lower levels has a direct effect on the interception of solar radiation and consequently on the energy savings contribution (Table 4). The knowledge about the growth pattern for the different species that can be used for green facades is a key point in order to face the design of this green infrastructure for energy savings purposes. In this regard, further studies for specific plants in specific locations must be conducted in the future.

The shadow effect of the double-skin facade can be observed in the thermographic pictures (Fig. 14). First, by comparison to the reference cubicle (Fig. 14A) where the overheating due to the direct incidence of solar radiation can be observed, and second, on the double-skin green facade (Fig. 14B) the differences between the East orientation, completely covered by vegetation, and the South orientation, on which some lacks of vegetation on the upper level, can be observed. The direct consequence of this lower coverage on the top of the South orientation was the major incidence of solar radiation and the overheating of that building surface.

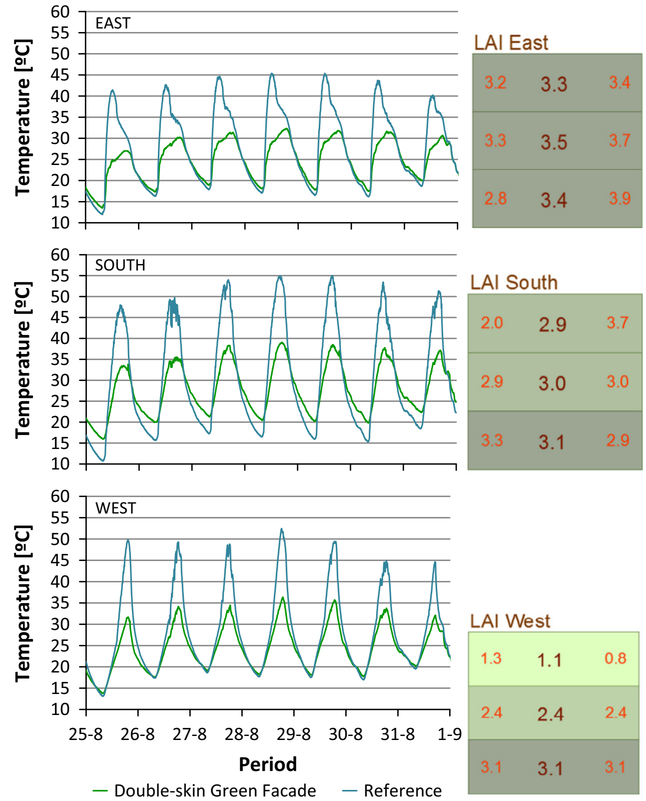


Fig. 15. Evolution of external surface building wall temperatures during the 4th week of August 2015 and related LAI values (measured values in red, average value in black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. LAI indirect measurement 2015

Fig. 15 shows the results for the calculated LAI according to Eq. (5), from the in situ measurements of PAR using a ceptometer. The figure shows the LAI values for each measurement point and the average value in each level for each orientation.

The LAI of the double-skin facade ranged between 1.1 and 3.5 on Summer 2015, and, as expected, a higher and homogeneous LAI was obtained in the East orientation. Recall that South and West orientations were replanted, thus their growth was slightly delayed with respect to the East orientation.

By comparing these values with those obtained in 2013 (Table 5) for the East orientation, it can be observed that the whole foliage density increased with height. Thus, although in the lower level the LAI value slightly decreases during the testing period, going from 3.9 to 3.4, in the middle and upper levels the LAI value increases, rising from 3.2 to 3.5 and 2.1 to 3.3, respectively.

Generally it can be concluded that, once completely developed, Boston Ivy (*Parthenocissus tricuspidata*) under Mediterranean continental climate achieves LAI values that range between 3.5 and 4. These values are quite lower than those obtained by Wolter et al. (2009) [18], where the LAI values were 7 for Ivy (Heredia helix) on East orientation and 8.51 on South orientation. Although these higher values, those authors state that the normal values range between 2.6 and 7.7. Relating to this, it is worth highlighting the different physiologic characteristics of these two species, because Ivy belongs to the perennial type and Boston Ivy belongs to deciduous type, and their growth pattern can be different.

In order to calculate the influence of these LAI values on the thermal behaviour, Fig. 15 also shows the evolution of the building facade wall surface temperatures by orientation for the two studied cubicles, the reference one and the double-skin green facade cubicle, for a representative Summer period week of 2015.

In this graphics the significant contribution of all orientations to the solar interception can be observed, with high reductions on the building surface temperatures compared to those of the cubicle without the green facade. To better understand these graphs, it should be taken into account that temperature sensors were located in the centre of the facade and therefore the obtained values corresponds to middle level LAI value for each orientation. The different contribution by orientation can also be seen, obtaining the highest solar radiation interception on the East facade, followed by South and West orientations.

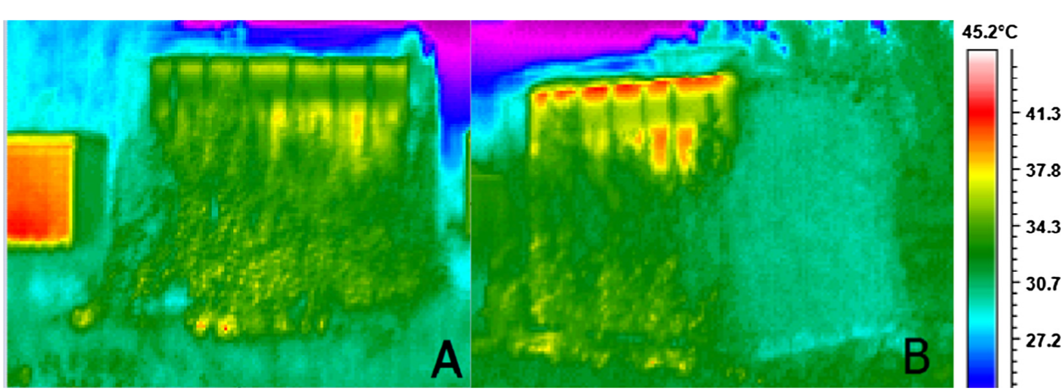


Fig. 14. Thermographic pictures. (A) The Double-skin green facade (centred) and the reference cubicle (on the left side). (B) Temperature and coverage differences between East (right) and South (left) orientations.

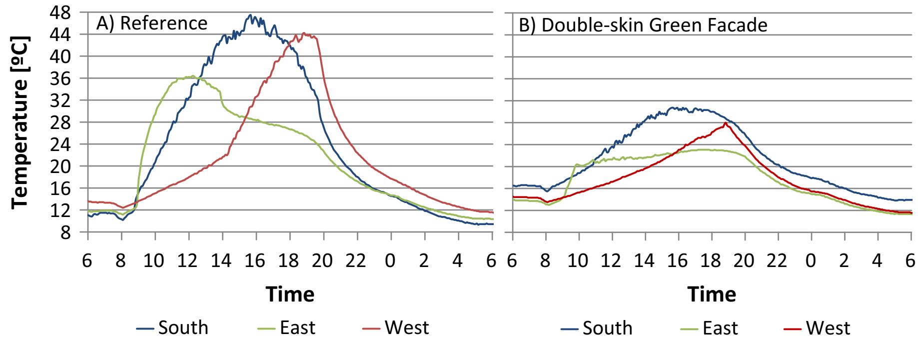


Fig. 16. Daily external wall surface temperature evolution by orientation. Summer 2015. Left: Reference cubicle. Right: Double-skin green facade cubicle.

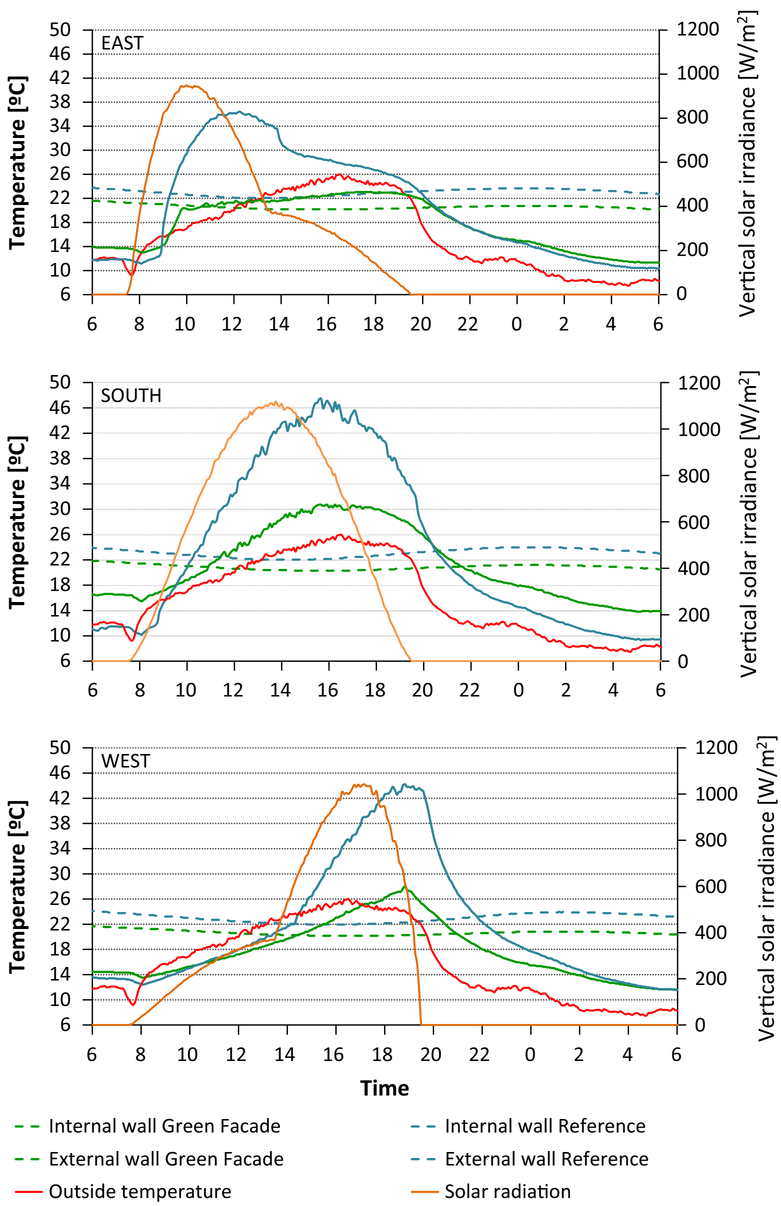


Fig. 17. Daily solar irradiance and internal/external wall surface temperature evolution by orientation. Summer 2015.

Fig. 16 shows a daily evolution of the external wall surface temperatures by orientation for the reference and the double-skin green facadecubicles. Fig. 17 shows a daily internal and external wall temperature evolution for each orientation, adding the solar irradiance.

Both Figs. 16 and 17 give an idea of how the green facade works in each orientation and what is the contribution by orientation to the reduction of temperature and consequent passive energy savings. On the East orientation the green facade is able to intercept the large impact of solar radiation in the early hours of the day with a reduction up to 15 °C on the wall surface temperature, going from a peak temperature of 36.4 °C to 21.4 °C (12:15 h), and maintaining temperatures below 23 °C throughout the day. On the other hand, the South orientation showed a reduction up to 16 °C during temperature peaks at 15:45 h. Finally, for the West orientation, reductions up to 16.4 °C were recorded, decreasing from the 43.9 °C to 27.5 °C at 19:00 h.

In view of these figures, it is also interesting to observe how the temperatures reduction occurs for each orientation. Thus, on the East orientation the green screen is not only able to eliminate the peak in the surface temperatures that takes place early on the morning, but also, to keep the building surface temperature under the 23 °C all day long. A large temperatures reduction takes place in the South orientation though following the same pattern as the reference cubicle. Finally, in the West orientation the green facade achieves significant reductions of the slope of the initial increase of superficial temperatures, reaching a considerably lower peak than in the reference cubicle. In addition, after the maximum value, the temperature drop is also faster than in the reference, i.e. at 22:00 h the building surface has still 23 °C while under the green facade the temperature is already 20 °C.

These results revealed that the shadow effect of green facade in the East and West orientations is quite significant and should be considered in an architectural design strategy with the same importance than for the South orientation. Therefore, the vertical greenery system provides dampened temperatures between internal and external air temperatures while maintain the same delay between inner and outer wall temperature peaks observed by orientation facades (thermal lag) of the building. These results complement and increase those provided by Jim [16], in which the contribution of VGS on the thermal performance of the buildings was highlight for a humid-tropical climate. In that study the big influence of the East orientation in reference to the South one was also found. Due to the experimental constraints no results were obtained for the West orientation.

Finally, in order to evaluate differences in the energy consumption of both cubicles (Double-skin green facade and Reference) an experiment under controlled temperature was carried out. The comfort range considered for the cooling period in Mediterranean continental climate is 23 °C and 26 °C based on the ASHRAE standards [30]. Therefore a set point of 24 °C was used to evaluate the thermal behaviour along this period. Fig. 18 shows the daily electrical energy consumption during the 4th week of August 2015. In this case, the cumulative energy savings obtained by the double-skin green facade cubicle was 34% lower at the end of the studied period in comparison to the reference cubicle.

This is a new and significant contribution to the energy savings in buildings that must be considered by architects and building designers in order to complement the traditional passive strategies with nature based solutions which allow achieving more sustainable urban environments.

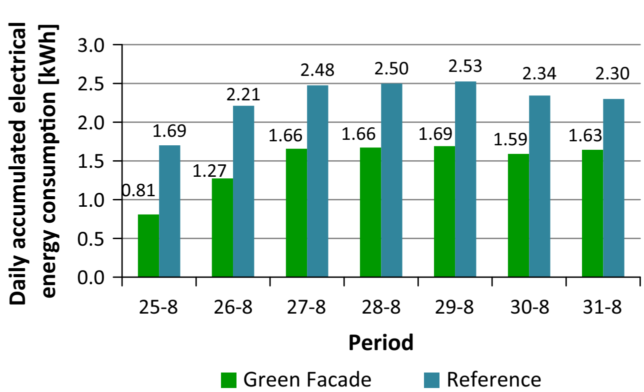


Fig. 18. Measured energy savings during the end of August 2015.

4. Conclusions

As continuation of a long term research in order to study the potential of vertical greenery systems as a passive tool for energy savings in buildings, a double-skin green facade made with a wire mesh light support structure and Boston Ivy (*Parthenocissus tricuspidata*) as deciduous plant species, was studied in an experimental cubicle under Mediterranean continental climate (*Csa, warm temperate - summer dry - hot summer*, according to Köppen classification) and compared to an identical reference cubicle without green screen. The influence of the leaf area index (LAI) and the building facade orientation on the shadow effect provided by the green facade as well as the relating energy savings on the cubicle were the main goals in this study.

From the literature review carried out it could be concluded that LAI is really a key parameter to characterize the foliar density and consequently the thermal behaviour of vertical greenery systems (VGS), especially for green facades, due to the big influence on the shadow effect. Despite this, a lack of data relating to LAI for the species used in VGS was found as well as of a suitable methodology to measure LAI for these purposes. After a theoretical approach to the LAI concept it could be stated that the most simple and quick procedure to measure LAI in order to characterize the foliar density of VGS is the indirect method, so that the resulting value can be related to its ability to intercept solar radiation.

From the results obtained in the experimental setup, it can be concluded that the double-skin facade can provide comparable shadow factor values for all orientations, to those provided by the artificial barriers proposed in building regulations such as facade setbacks, cantilevers, awnings, slats, and others (Table 4).

As a consequence of this capacity to intercept direct solar radiation the experiments with no HVAC systems conducted during Summer 2013, when the green facade was only partially developed, showed the high capacity to intercept the direct solar radiation, which implies representative reductions on the external surface wall temperatures up to 10.1 °C on the South orientation, and indoor temperature reductions around 2.5 °C.

On Summer 2015, with a higher foliage development, this thermal behaviour was confirmed by representative reductions on the external surface wall temperature in all orientations (East, South and West). In addition, tests under controlled temperatures showed the high potential of the double-skin green facade as a passive system in comparison to the reference one, obtaining accumulated electrical energy savings up to 34% for cooling periods with a LAI of 3.5–4 during the Summer period, under Mediterranean continental climate.

In addition, it was confirmed that the energy savings provided by green facade systems are dependent on the orientation. Thus, on the East orientation the green facade was able to intercept the large impact of the solar radiation in the early hours of the day with a reduction of 15 °C on the building surface temperature, going from 36.4 °C to 21.4 °C at 12:15 h, and keeping it below 23 °C throughout the day. In the South orientation, at the time of peak temperatures in this orientation (15:45 h), the reduction was up to 16 °C, going from 46.7 °C to 30.7 °C. Finally, on the West orientation the double-skin green facade was able to reduce 16.4 °C, going from 43.9 °C to 27.5 °C at 19:00 h.

Results revealed that the shadow effect of green facades on the East and West orientations is representative and should be considered in architectural design strategy with the same importance than South orientation.

Generally it can be concluded that, once completely developed, Boston Ivy (*Parthenocissus tricuspidata*) under Mediterranean continental climate achieves LAI values that range between 3.5 and 4.

The findings of this research contribute to the consolidation of VGS as one of the most promising nature based solutions for energy savings in the built environment, as an alternative to traditional grey solutions.

Acknowledgements

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