Thermal behaviour assessment of a novel vertical greenery module system: first results of a long-term monitoring campaign in an outdoor test cell

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Thermal behaviour assessment of a novel Vertical Greenery Modular System: first results of a long term monitoring campaign in outdoor test cells

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Bianco Lorenza[1]; Serra Valentina[1]; Larcher Federic[2]; Perino Marco[1]

[1]TEBE Research Group, Energy Department, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy

e-mail: valentina.serra@polito.it

[2]DISAFA, Università degli Studi di Torino, Grugliasco, Torino, Italy

Abstract

Vertical Greenery Modular Systems (VGMS) are an increasingly widespread building envelope solution aimed at improving the aesthetical quality of both new and existing façades, contemporarily achieving high energy efficiency performance. Within a research project a new prototype of VGMS was developed, designed and tested. An experimental monitoring campaign was carried out on a test cell located in Turin (northern Italy), aimed at assessing both biometric parameters and energy related issues. Two different types of growing media and two plant species, *Lonicera nitida* L. and *Bergenia cordifolia* L., have been tested on a south facing lightweight wall. Results have been compared to the same wall without VGMS and plaster finished, in order to characterize the thermal insulation effectiveness in the winter period and the heat gain reduction in the summer period. Measured equivalent thermal transmittance values of the green modular system showed a 40% reduction, when compared to the plastered wall, thus noticeably impacting on the energy crossing the façade during the heating season. Benefits of the VGMS are measured also during the summer season, when the presence of vegetation lowers the outdoor surface temperatures up to 23°C compared to the plastered finishing, with a positive effect on outdoor comfort and urban heat island mitigation. Nevertheless not significant reduction was observed as far as the entering energies are concerned, since the green coverage acts as a thermal buffer and solar radiation is stored and released slowly if compared to the plastered wall.

Keywords: vertical greenery modular system, green wall, green façade, living wall, energy performance, LAI, vegetation species.

Introduction

The use of vegetation in buildings to minimise cooling loads in summer and to improve thermal insulation in winter is a diffused strategy and it is widely adopted by designers (Hoyano 1988, Manso and Castro-Gomes 2015). Starting from the green roof, which is a well-established technology, various alternative solutions, in order to "vegetate" also the vertical walls have been recently developed (Perez et al. 2011). These systems, such as living wall and Vertical Greenery System (VGS), integrate green living elements in buildings façades in different ways. In particular, a new generation of green walls, realised with green modular components, is becoming widespread in the building components market, due to the fact that they can be directly positioned on the wall and easily substituted in case of plants disease. Following the classification of the recently published review of Manso and Castro-Gomes (2015), these kind of systems are named Vertical Greenery Modular Systems (VGMS) and are typically composed by a supporting element, a growing media, vegetation and an irrigation system.

From the thermophysical point of view, the green systems act both as a solar shading barrier on the façade and as an extra insulation layer (Safikhani, T. et al. 2014). As far as the summer behaviour is concerned the use of a vegetated vertical wall contributes to reduce the internal surface temperature and consequently to increase indoor thermal comfort (Papadakis et al. 2001). The solar radiation incidents on the plants is partially reflected, partially used for the biological activities of the plant such as evapotranspiration and photosynthesis and partially stored by the lymphatic system (Ariaudo et al. 2009). The shading property of the leaves has a positive effect during summer but may be negative during winter since the solar heat gain is reduced. Regarding this aspect, non-south facing façades were studied by simulation, in order to investigate the effect of green wall orientation. Results showed the greatest cooling loads reduction for green layer applied on east - or west-oriented surfaces (Kontoleon and Eumorfopoulou 2010).

During the winter season, vertical green systems can reduce the external heat transfer coefficient of surfaces by lowering the wind velocity (Perini et al. 2011). In this way the vertical green element can play an important role also during the heating season. Simulation results showed, as expected, a linear correlation between shading coefficient and leaf area index (Wong et al. 2009). Results of a sensitivity analysis evaluated that the plant with dense foliage and with leaves parallel to the wall are the most effective in reducing surface temperatures and heat fluxes through the façade.

At the building level Perez et al. (2016) published the results of in situ measurements of VGS demonstrating an improvement of the wall sound insulation with the application of a thin layer of vegetation (20–30 cm).

Moving to the urban scale an extensive coverage of the surfaces exposed to solar radiation can thus significantly reduce the urban heat island effect (Alexandri and Jones 2008). Evapotranspiration and leaves shading effects, can modify the microclimate close to the green wall by reducing relevantly the external air temperature (Wong et al. 2010 and Hoelscher et al. 2015). In a recent work, the thermal performance of different green wall systems, in tropical climate, was measured. Results showed the cooling effect on the air temperature of the immediate external environment and the reduction of the surface temperature due to vertical greenery system (Chen et al. 2013). Simulation performed with a new numerical model investigated mitigation measures to limit urban heat island effect (Saneinejad et al. 2014). The overall results showed that evaporative cooling can considerably reduce the air temperature and the mean radiant temperature, but shading is the measure which allows to reach the highest level of thermal comfort. Recently new mathematical models, validated against experimental data, were developed to perform simulation on vegetated exterior façades (Susorova et al. 2013) and to assess their impact in dense urban context (Djedjig et al. 2015).

The VGS benefits are therefore also transmitted to the urban scale, where they can also act positively on the urban sound propagation, mitigating the classical "acoustical canyon effect" produced by multiple reflections of sound in cities streets framed by buildings (Ismail, 2013 and Candelari et al. 2013). An experimental study analysed different VGS, to evaluate their acoustics impact (Wong et al. 2010). Results showed a strong attenuation at low and middle frequencies due to the absorbing effect of the substrate while at high frequencies a smaller attenuation is observed due to scattering phenomena on the greenery. Another simulation study demonstrated that vegetated façades are most efficient when applied to the narrow city canyons and that to achieve a better soundscape the combination of green roofs or vegetated walls with roof screens seems most performing (Van Renterghem et al 2013).

Moreover other studies observed that the vegetation is able to filter polluted air and to clean it by capturing particulate matter (Ottelè et al. 2010). As far as air pollutants are concerned, the air pollution tolerance index (APTI) for different climber plant species for VGS application is evaluated in Pandey et al. 2015. Related to the air quality the capability of green wall to sequester CO_2 is investigated in a review (Charoenkit and Yiemwattana 2016) showing the effectiveness of this technology but a poorer performance if compared to green roofs.

Vegetated walls have been also promoted because aesthetically pleasing. It was demonstrated by two experiments that effectively the majority of people preferred building with façade integrating vegetation (White et al. 2011).

In general, from the literature review it can be stated that the effects on building energy demand, surface temperature control and external air quality are closely connected to substrate properties and plants characteristics: type of foliage, deciduous/non deciduous leaves, density of covering ratio (LAI) and evapotranspiration regime. However, only few studies concerning the thermal effectiveness of this technology during the whole year are available (Mazzali et al. 2013, Perez et al. 2014 and Manso and Castro-Gomes, 2016). Furthermore, VGS thermal behaviour seems to be strictly dependent on the plant species characteristic and the substrate type used (Charoenkit and Yiemwattana 2016). Some experiments have been carried out to characterize different plant species for green walls application but they are the results of a monitoring activity in a controlled environment facility (Cameron et al. 2014). The results of the tests in controlled indoor environments, in addition to confirm the cooling potential of green walls, demonstrate that the cooling mechanism is strictly connected to the type of plant species. Data concerning *Lonicera* were obtained in the indoor facility and the analyses, presented a shading cooling potential of the plant which corresponds to a temperature reductions of 5.5 °C, if compared to a reference wall. As far as the growing media is regarded, different studies have been carried out on green roofs demonstrating that the thermal behaviour of the system could vary depending on different substrate compositions and depth (Coma et al. 2014).

In this framework a long-term monitoring activity has been carried out on a Vertical Greenery Modular System (VGMS) (following the classification of Manso and Castro-Gomes, 2015) in order to collect data concerning different plant species and growing media, as far as both biometric aspects and energy related issues are concerned.

Background and aims of the research

Within a regional funded research project a new prototype of Vertical Greenery Modular System (VGMS) was developed, designed and tested. Different partners, with industrial and academic background, worked jointly in the project, focusing on the integration of vegetation on a patented prefabricated lightweight modular system (BYBOX®, CEIT, Asti, Italy), mainly devoted to the Piedmonts market (Northern Italy). The challenge was to design a VGMS, highly performant from the energy point of view, easy to be installed and maintained and cost effective. The high energy efficiency was related both to the operational energy (heating and cooling demand reduction) and the embodied energy. A key factor was in fact the low environmental impact of the system, achieved using recycled materials. During the design phase a simplified Life Cycle Assessment was employed with the aim of identify the most ecological materials to constitute the module (Serra et al. 2014).

The activity here presented is related to the first phase of the project where some data concerning biometric issues and energy behaviour of the newly developed VGMS prototypes were collected through a monitoring campaign in nursery and in outdoor test cell. Results were then used in the second stage of the research, in order to identify the most appropriate solution to be installed in a full scale mock up in Torino (Northern Italy).

As far as the experimental activity carried out in an outdoor test cell is concerned, it was mainly focused on:

- the assessment of the thermal behaviour of the VGMS applied to the lightweight insulated envelope compared to the same wall when plastered, especially focusing on heat fluxes transmission and on surface temperature control;
- the investigation of the influence of different plant species and substrates on the thermal behaviour of the module. Two species, characterised by different LAI (leaf area index), and two different substrates were chosen, according to the results coming from the research activity previously carried out in a garden nursery.

Materials and methods

A modular system consisting in 40x50 cm panels and 4 cm depth, hanging on metal supports was investigated. The VGMS was composed as follows: a frame of galvanized aluminium, two layers of rootable nonwoven synthetic mats and two geogrids. In each panel 6 pockets were cut out to host one plant each (Fig.1).

Three different substrates were trialled, one standard (named SS) and two novels (named SF50 and SF 50B), composed by the traditional substrate SS added with chair felt, deriving from an industrial residue of a local production, thus contemporarily recycling a waste material and exploiting its features as hydroretentor. The SF 50 and 50B presented the same composition with the felt otherwise worked. In detail the following substrates were tested:

1. SS = standard substrate (coconut fibre + hydroretentors + mycorrhizae);

2. SF50 = 50% standard SS + 50% shredded felt;

3. SF50 B = 50% standard SS + 50% shredded felt +felt pads;

The third substrate (SF 50B) was just tested to evaluate the LAI and the biometric parameters of the plants.

In order to test the suitability of the felts in this new role and to identify the best combination of plant and substrate, two different evergreen and perennial shrub species, *Lonicera nitida* L. and *Bergenia cordifolia* L. were adopted and compared. Both plant species, commonly used in urban greening in Europe and suitable for extreme air temperature up to -15°C /-20°C were previously tested in a lab nursery, located in a vertical position. *L. nitida* is a well-established species for living walls and provides a good cover effect with its little leaves, while *B. cordifolia* was not yet tested in living wall and its effect is completely different for the big and thick leaves and showy flowers (Fig. 2). The species were chosen also for their low maintenance cost: generally the species are pest free and they must be pruned once per year (Royal Horticultural Society).

Three modules for each combination of species and substrate were mounted in the test box and data concerning boundary conditions were continuously collected. Surface temperatures and heat fluxes of two modules located in the central row (SS and SF50 + alternatively *Lonicera nitida* L. and *Bergenia cordifolia*) were also monitored for the energy assessment purposes. Measurements started during winter and were carried out during different seasons.

The test box, located on the roof top of the Energy Dep. of Politecnico di Turin[1] (Italy), was specifically built up by one of the industrial partner involved in the research project. The test box was made according to its patented system, with a conventional envelope, described in Table 1, presenting a thermal transmittance of 0.3 W/(m^{2}K) and 20 cm thickness, in accordance with the national and regional standard related to energy efficiency in buildings. A section of the assembly of the test box is shown in figure 3. It is constituted by: an external plaster finishing, a wood structure, a polystyrene insulation panel, a wood structure, a non-ventilated cavity with a polyester insulation and a wood structure.

The dimensions of the test cells (2 m x 1.8 m x 1.8 m external gross measures) were defined in order to maintain the internal temperature through the ventilation air which was re-circulated by another experimental apparatus. This apparatus was used in the same period for other research purposes and it had the same internal temperature requirements. The air temperature was maintained with a full air HVAC system (temperature tolerance ±1°C). The set-point of the indoor air temperature during winter was 20°C while during summer the indoor temperature was in free-floating conditions.

South orientation was chosen for the tested VGMS and reference wall, in order to have a high amount of solar radiation on the plants. The south façade (2 m x 1.8 m) was differently finished: part of the external insulation layer was conventionally plastered (bare wall) and it was considered the reference wall and part was covered with the VGMSs constituted by three vertical stripes for each module (Fig. 4).

In order to maintain a good growing performance of the plants, in accordance with the standard practice, during the summer season the automatic irrigation system was activated adding nutrient in the water. The modules were irrigated every 2 hours for 2 minutes, while during winter no irrigation was supplied. A micro drip irrigation system for each level of the green modules was provided. Care was taken to avoid the possibility that the lower panel would not receive water (Figs. 4 and 5).

Performance metrics

Biometric parameters

As demonstrated in literature heat transfer and temperature control depend also from the substrates of the plant (Coma et al. 2014 and Manso and Castro-Gomes 2015). The leaves shape, number and surface are species characters but the growing media, together with the environmental conditions, can modify them.

[1] 45.05 N - 7.67 E, northern hemisphere, a humid subtropical climate following Köppen climate classification Cfa.

For indirect measure of leaf chlorophyll content and therefore differences in leaves characters between the two species tested, the Chlorophyll Meter SPAD-502 Konica Minolta (Nieuwegein, Netherlands) was used (Smith et al. 2004). SPAD indexes were performed on 4 leaves randomly chosen within 10 plants for each species (*L. nitida* and *B. cordifolia*), being each measure the mean value of 2 measures on the same leaf.

At the end of the first vegetative period (in November), the aerial part of 12 plants for each species and substrate was oven-dried at 90°C for 48 h. Fresh and dry weights of leaves were determined and the humidity rate (%) was calculated in order to define the main differences in leaves compositions between the two species.

To investigate the influence of the plant species on the environmental parameters, leaf number (L) and leaves area (LA) of six plants for each combination of species and substrate were calculated.

The leaves were cut at the end of the first vegetative period (during October) when plants are assumed to have the best covering and ornamental value.

Leaves measurement were performed scanning all leaves with a standard A3 scanner and the scanner *Xnview* free software (version 1.98.2/1.70 by Gougelet P., Reims, France) was used. Images were properly modified and leaves number and geometry data (area and perimeter) were automatically calculated by using *ImageJ* free software (version 1.45m by Rasband W., Bethesda, Maryland, USA).

The leaf area was also used to calculate the Leaf Area Index (LAI) that was defined by Watson (1947) as the total one-sided area of leaf tissue per unit ground surface area (Brèda N.J.J., 2003). It is a dimensionless quantity, which was less used for living walls. In this trial the Leaf Area Index for one module (LAI) was calculated using equation (1):

$$LAIm = LA / A_m \qquad (1)$$

where LA was the total leaf area [mm^2] of the six plants grown on one module and A_m was the area of one module (500 mm x 400 mm).

Thermal performance

To characterise the envelope thermal performance, the green modules and the plastered wall were contemporarily monitored. The measurement equipment consisted of 16 sensors connected to a data-logger that recorded data every 15 minutes. The thermocouples were preliminary calibrated in laboratory and all the other instruments were previously tested. The measurement accuracy of each thermocouple was assessed according the SIT standards, considering the uncertainties of the reference thermoresistance and of the thermostatic bath used during the calibration. As result of this procedure, the highest likely uncertainty, using the 95% confidence limit, was ±0.3 °C. This value was conservatively adopted for all the thermocouples.

Hukseflux HFP01 sensors characterised by thermal resistance lower than 6.25 10^{-3} (m^2K)/W were used to measure the heat flux. As declared by the manufactures, their measurement accuracy was ±5 % with a confidence interval of 95 %, while the nominal sensitivity was of about 50 μV/W/m^2 .

In detail, the sensors used during the experimental campaign are represented in the schematic plan of the box in Figure 6. Boundary condition were recorded by means of indoor (T_air_int) and outdoor (T_air_ext) thermocouples to measure the air temperature. The solar radiation on the façade was registered by a vertical pyranometer (I_OUT_V). Two heat flux meters where applied to measure the heat flux through the green and plastered wall, positioned on the inner surface of the wall (respectively named HF_R and HF_V). Internal surface temperature was measured for the reference wall (T_si_R) and the VGMS wall (T_si_V). To detect surface temperatures in the rear of the VGMS three thermocouples were positioned (T_mid_A, T_mid_B, T_mid_C). On the outer side of the VGMS the external surface temperature of the green modules was registered (T_se_A, T_se_B, T_se_C). At the same level the external surface thermocouple of the reference wall was positioned (T_se_R).

The experimental activity started measuring the reference technology against the wall without the VGMS, i.e. bare wall versus the same technology without the external finishing. The heat fluxes measured were compared in order to verify that the dimension of the reference technology was sufficient to avoid borders effect. The results showed that the difference between the two walls were in the order of the heat flux meter error.

The collected data were thus processed and surface temperature profiles and daily energy were analysed. To facilitate the analysis of the performance of the VGMSs the attention was focused on a typical winter and summer day.

The convention used during measurements is that a negative value of heat flux means heat losses and a positive value means heat gains. The same convention was used to calculate the daily energy.

Daily energies were calculated as the integral of the heat fluxes ($\dot{q}$) measured along the day (equation. 2).

$$E = \int_{24}^{00} \dot{q}\,(\tau)d\tau \qquad [Wh/m^2] \qquad (2)$$

Furthermore, to compare the equivalent thermal conductance (C*) of the different VGMSs and that of the plastered wall, the progressive average methodology was applied. The average values of the specific heat flux ($\dot{q}$) and the surface temperature differences, were used instead of the instantaneous values (ISO 9869, 1994), according to equation (3). Similarly, the equivalent thermal transmittance (U*) of the tested technologies (both the reference bare wall and the wall with the VGMS) was evaluated (4), considering the average value of the specific heat flux (3a) and the temperature difference between internal and external air (3b).

$$C* = \frac{\overline{(\dot{Q}/A)_n}}{\overline{(\Delta T_s)_n}} \quad [W/(m^2°C)] \quad (3)$$

Numerator: $\overline{(\dot{Q}/A)_n} = \sum_{i=1}^{n} (\dot{Q}/A)_i$ [W/m^2] (3a)

Denominator: $(\overline{\Delta T})_n = \sum_{i=1}^{n} (\Delta T)_i$ [°C] (3b)

$$U* = \frac{\overline{(\dot{Q}/A)_n}}{\overline{(\Delta T)_n}} \quad [W/(m^2°C)] \quad (4)$$

Because of the dynamic behaviour characterising the VGMSs, it is not a simple task to provide a synthetic index, that would be useful to compare different species and substrates. Data elaboration results showed that the progressive average method could be a suitable methodology for determining the conductance and the transmittance values of the different technologies tested.

In addition, the difference between the two technologies, i.e. bare wall and VGMs, was investigated evaluating the surface thermal resistance. According to equation (5) the sum of surface thermal resistance, internal and external, was calculated as the difference of the inverse ratio of the thermal transmittance and the thermal conductance.

$$R_{si} + R_{se} = \frac{1}{U*} - \frac{1}{C*} \quad [(m^2K)/W] \quad (5)$$

Analysis and discussion

Biometrics parameters

SPAD values quantify how much the leaves of *L. nitida* are greener than the ones of *B. cordifolia*, 51 and 38 respectively. This index can have an impact on the solar radiation absorbtance and consequently it may affect the VGMS surface temperature. In this study it was not possible to properly investigate this correlation since the results are due to a combination of factors including LAI and number of leaves. Further investigations on this aspect are currently on going.

The results of plants measurements are reported in table 2 and 3. Leaves' number (L), mean Leaf Area (LA) per plant and Leaf Area Index for one module (LAI_m) are calculated with the mean values of the six selected plants.

In table 2 data on dry weight and humidity ratio, analyzed together with the number of leaves and the LAI index (table 3), demonstrate that *B. cordifolia* produces a biomass and leaves with a water content higher than *L. nitida*. But *L. nitida* species produces a high number of little and dry leaves creating a thicker vegetative pillow on the wall.

As expected results show that *L. nitida* leaves' number are many more than *B. cordifolia* ones for both the substrates tested. In *L. nitida* the effect of the presence of the felt pads shows a slightly higher number of leaves in plants grown on SF50 substrate than in SS substrate while it is not observed such a relevant difference for *B. cordifolia* between the two growing media. For *B. cordifolia* it was registered a higher leaf area index than for *L. nitida* .

Considering the differences in the *habitus* of the species, it can be said that the felt pads had an effect in increasing the aerial part of the plants and that *B. cordifolia* is in a greater extent influenced by the felt than *L. nitida.* Also, the LAI_m is higher in plants grown on SF50, compared with SS.

Considering the good results on *L. nitida*, recently other ornamental shrubs have been selected for living walls in Mediterranean climatic conditions (Devecchi et al., 2013). These species are suitable for dry and hot conditions and their energy effects on buildings could be further tested.

In LAI index, some properties of the vegetative part of the plant are not considered; the overlapping and the thicknesses of the leaves of the plants are a missing information. For this reason, further researches on the parameters to characterize the VGMS plant should be carried out.

As a general comment it was possible to observe that no problem on long period installation were noticed for the *L. nitida* while *B. cordifolia* showed some weaknesses due to the vertical position on the wall.

Thermal performance

Winter conditions

During the winter period the capability of the green modules to reduce heat losses was investigated. The shading effect of the leaf coverage could have a negative effect on the energy balance of the wall covered with VGMS due to a reduction of the solar heat gains. On the other hand, the green system should be able to reduce the heat losses thanks to the capability of the leaf coverage to reduce the air movement on the surface hence to modify the convection and radiation coefficients (Eumorfopoulou et al. 2009).

Typical winter sunny day (L. nitida).

The boundary conditions (

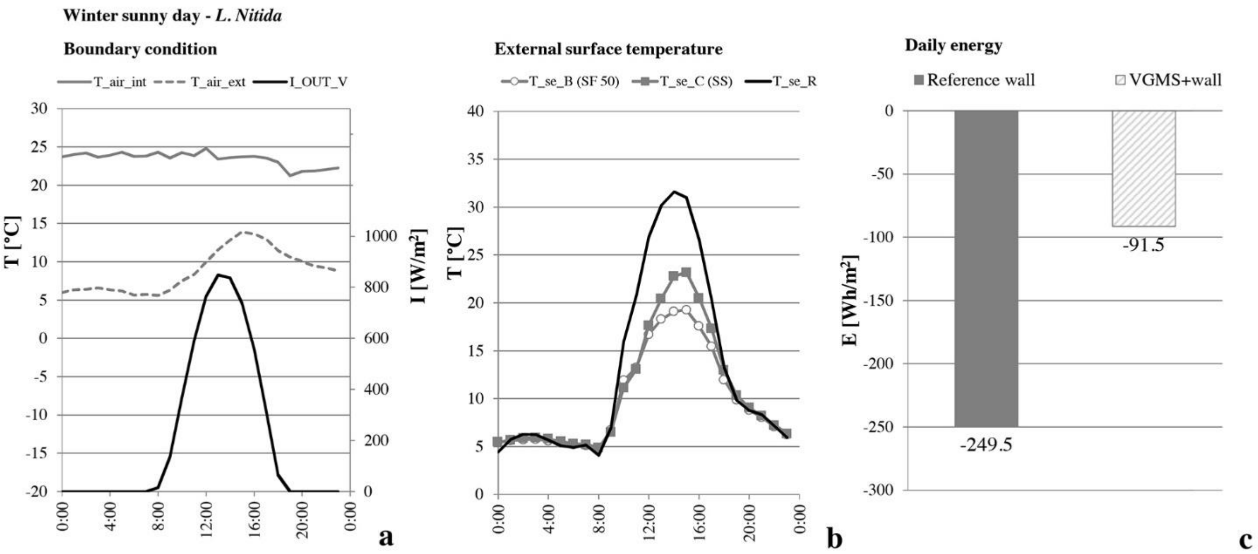

Fig 7a) during the winter sunny day showed a maximum air external temperature of 14 °C, a minimum temperature of 5.6 °C and an average daily temperature of 8.8 °C. The average internal test cell air temperature was 23.4 °C. The solar irradiance showed a maximum value of 847 W/m^2 at 1 p.m. During the day, the surface external temperature of the plastered wall reached a maximum temperature of 31.5 °C while the surface temperatures of the green modules were 8 °C lower due to the shading effect of the leaves (

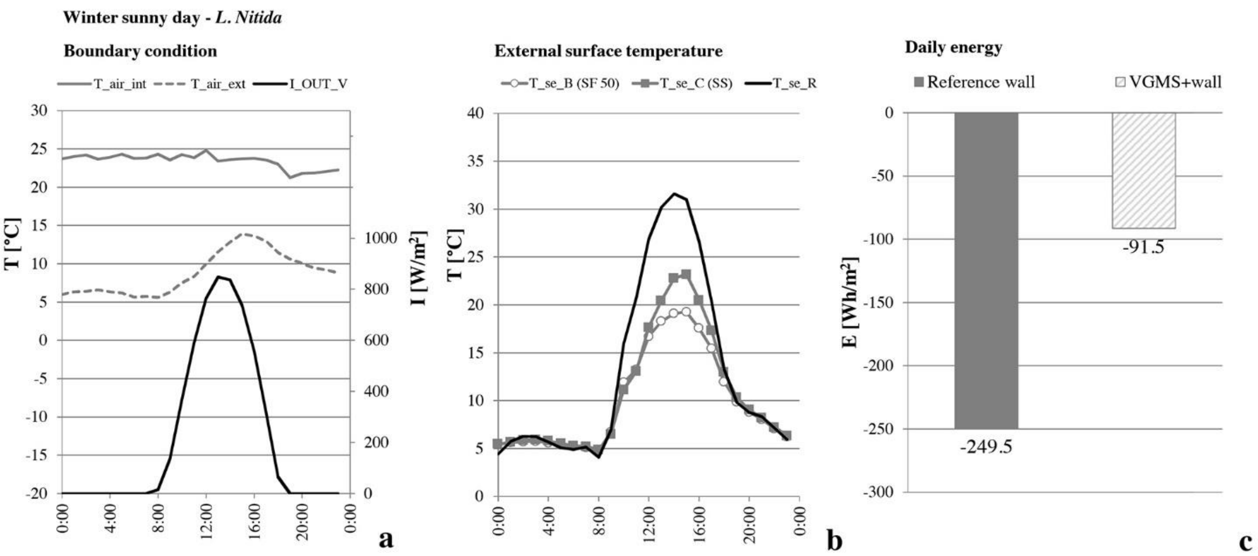

Fig 7 b).

The heat fluxes registered through the reference wall and the green wall were negative during the entire day. Therefore, both the reference wall and the VGMS were characterised by heat losses. The green wall heat fluxes were significantly smaller than the ones of the plastered wall and from the analysis of the daily energy the green contribution was thus quantified. The total daily energy of the green wall was 91.5 Wh/m^2 while the bare wall showed a higher value 249.5 Wh/m^2 (Fig 7c). These results demonstrate that the green prototypes positively influence the winter behaviour of the system by reducing the heat loss of 63% compared to a conventional plastered wall. It can be stated that the green coverage did not reduce the solar heat gain exploitable by the façade in a relevant way, because the heat fluxes through both the wall typologies were very similar during the afternoon (high solar radiation). Furthermore the green system was providing an extra thermal insulation. This result is in line with the experimental activity carried out on a modular green wall in a Mediterranean climate by Manso and Castro-Gomes, (2016) who evaluated a reduction of the 60% of the outgoing heat flux.

Typical winter cloudy day (L. nitida).

The boundary conditions (Fig. 8a) during the winter cloudy day are here summarised: the external air temperature had an average value of 4.4 °C, the average internal air temperature in the test cell was 20 °C and the solar irradiance showed a maximum value of 67 W/m^2 at 10 a.m.

The external surface temperature of the bare wall was higher than those of the green systems during the entire day (Fig. 8b). The temperatures measured in the rear of the module by the thermocouples placed between the green modules and the wall (T average MID), are shown in Fig. 8b as an average value of the three readings (behind VGMS A, B and C). This temperature was higher than the surface ones. During the night and in the early morning the temperature difference between the surface and the middle layer was maximum (up to 3°C). This means that the air layer behind the green modules was kept warmer hence creating an additional insulation layer.

As expectable the heat fluxes profiles during the cloudy day, are negative for both the wall systems and they present an average values of around -5 W/m^2 for VGMS and -10 W/m^2 for bare wall. Daily energy showed that during a cloudy winter day the green system can reduce heat losses of about 56 % when compared to the plastered wall (Fig. 8 c).

Winter days (B. cordifolia).

The same trend registered during winter for *L. nitida* is monitored for *B. cordifolia*. The selected period is constituted by four late winter cloudy days that do not present higher solar irradiance value than 220 W/m^2 (Fig. 9). Surface heat fluxes crossing VGMS with *B. cordifolia* are close to zero while the reference wall presents lower values around -10 W/m^2. The daily energies show values for the VGMS+wall between -60 Wh/m^2 and -75 Wh/m^2 (Fig. 9 b) against reference wall values between -190 Wh/m^2 and -236 Wh/m^2. As for the *L. nitida*, the wall with *B. cordifolia* presents lower thermal transmission during the entire period.

Winter insulation efficiency

In order to characterize thermal behaviour of the VGMS and the bare wall data collected during winter season were analysed by calculating the thermal conductance and transmittance with the progressive average method (equation 3 and 4) for both *L. nitida* and *B. cordifolia* (Table 4).

The final values of C* and U*, evaluated through the average method, do not deviate +/- 5% from the value obtained 24 h before. This means that the calculated values of U*/C* are stabilized and the validity conditions imposed in the ISO 9869 1994 are verified.

Thermal transmittance and conductance of the VGMS are lower than bare wall values, confirming the better performance of the VGMS observed in the previous paragraphs, analysing heat fluxes and energy. For the reference wall it was calculated an average U* value of 0.60 W/m^{2}K and an average C* value of 0.39 W/m^{2}K. No particular differences were calculated between the two plants species since a U* value of 0.17 W/m^{2}K was calculated for both *L. nitida* and *B. cordifolia*. A slightly difference was calculated for the C* value with 0.22 W/m^{2}K for *L. nitida* and 0.21 W/m^{2}K for *B. cordifolia*. In both cases VGMS presented lower thermal conductance and transmittance than the bare wall, for both plant species. This can be caused by two effects: the extra insulation deriving from the presence of the modular panel in front of the wall and the foliage that increases the surface thermal resistance of the system. This second point was investigated through the surface thermal resistances calculation, as showed in equation 5. Resultant surface resistances values (Rse + Rsi) for VGMS are higher than the ones for the bare wall. The difference between green coverage and bare wall is around 0.42-0.31 (m^{2}K)/W. It is indeed possible to state that the presence of vegetation on a façade, increases noticeably the surface thermal resistance if compared to a standard plastered wall. This result was moreover confirmed in the full scale mock up measurements, carried out by the Authors in the second stage of the research and currently under investigation.

Unfortunately, it was not possible to define the thermal performance of the different substrates separately. Some experiments were conducted in laboratory with a hot box to evaluate the thermal conductivity of the three panels without vegetation. It was not found a relevant difference between panels containing standard substrate SS and the substrate with felt SF50. Thermal conductivity values monitored, for dry samples, varied actually between 0.09 W/(mK) and 0.11 W/(mK).

Summer conditions

In the summer period the analyses were aimed at evaluating the effect of VGMS on external surface temperature and on the reduction of the entering heat flux and energy.

As far as the external surface temperature is concerned, the green modules presented values significantly lower if compared to the plastered wall. In figure 10 results concerning six consecutive days are plotted, showing the surface temperature of both the VGMS (*L. nitida*) and the bare wall. The peak temperature reduction reached 23 °C (Fig.10). Considering the daily average surface temperature, the difference between the VGMS and the plastered wall was around 7 °C. These data indicate the cooling effect of the green modules and they confirm the results collected in cabinet by Cameron et al. (2014). During the night both surface temperatures decreased to the same value around 6 a.m. while the highest temperature was reached in the afternoon at 2 p.m for the bare wall and two hours later for the VGMS.

Comparing the surface temperatures profiles, a different temperature decrease trend between the VGMS and the plastered wall was observed. The temperature of the green modules started to decrease at a later time in the afternoon. The experimental apparatus was not able to evaluate the latent heat due to evapotranspiration, neither to evaluate separately the hygric dynamic behaviour of the plants related to the irrigation, hence purely qualitatively considerations can be done.

The boundary conditions during a typical summer day (maximum external air temperature 31°C, minimum temperature 17.9 °C, average daily temperature 23.8 °C and maximum value of solar irradiance 705 W/m^2, measured at 2 p.m) are presented in Fig. 11a. The internal air temperature fluctuated between 20°C and 28°C, (daily mean value 23.1°C). The analysis of the energy crossing the plastered wall and the green wall showed a slightly worse behaviour of the VGMS, where entering energy was measured. It is important to stress that the heat fluxes were very low and the values registered were in the field of error of the heat flux meter. Low thermal transmission was due to the high insulation properties of the reference wall, respecting the U-value national standard limit. It is anyway possible to draw some conclusions since a repetitive behaviour was registered. The green wall creates a warm cavity which acts as a thermal buffer, thus increasing the thermal inertia of the system and releasing heat slower than the plastered wall. Integrating the heat fluxes (as shown in Fig.11b), it resulted that through the green wall an entering energy (+12.4 Wh/m^2) was monitored, whilst through the plastered wall an energy loss (-19 Wh/m^2) was registered.

Conclusions

This experimental study investigates the thermal behaviour of a vertical greenery modular system (VGMS) applied to a lightweight insulated wall. Its behaviour is compared with the same wall, with a plaster finishing. Furthermore, the use of a substrate with standard potting compost mixed with insulating materials from industrial residue (felt coming from the production of chair felt pads) is investigated.

The comparison is carried out through the analysis of the experimental data collected during one year of measurement campaign, where the *L. nitida* and *B. cordifolia* species were tested. The discussion of the results pointed out the efficiency of the system during the heating season. The green modules applied on the wall are able to reduce heat losses and to create a warmer insulating air layer between the wall and the prototype, thus reducing for both species the energy crossing the wall in the range of 37%-44%.

In accordance with these results thermal transmittance values were calculated, providing a value of, 0.17 $W/(m^2K)$ for both the species against about 0.40 W/m^2K for the bare wall. In addition, it was calculated that the presence of vegetation improves significantly, in the range of 0.42 – 0.31 $(m^2K)/W$, the external surface thermal resistances of the VGMs compared to the reference plastered wall. These results are in line with other researches (Serra et al. 2014 and Perini et al. 2011).

During summer the potential of the green modules in reducing urban heat island effect was demonstrated through the observation of a noticeable reduction of the peak external surface temperatures. Heat flux data collected during the hot season were not completely reliable because they were too low and in the range of the sensor error. In any case, the analysis of repetitive and justifiable trends made it possible to state that the green module creates a warm cavity in the rear of the module acting as a thermal buffer and releasing heat to the internal environment more slowly than the plastered wall and causing higher entering daily energy. Further analysis on a full scale mock up showed that, enhancing the ventilation behind the vegetated modules, an improvement on the summer performance can be achieved (Serra et al. 2014).

As far as the substrates are regarded, it is possible to conclude that the presence of felt pads increased the aerial part of the plants. On the contrary no particular advantages were registered on the thermal performance of the VGMS.

As a general conclusion, considering the biometric parameters it is possible to state that both species *L. nitida* and *B. cordifolia* are suitable for VGMS. Nevertheless it is important to underline that the long term experimental campaign demonstrated that the main drawbacks were pertained to *B. cordifolia*. In fact during heating season worst aesthetic aspect of the VGMS was observed due to icing of leaves, which appeared burnt.

Moreover, the designer of VGMS usually includes different species of plants on the same wall and therefore these results are to be considered as a decision support tool to identify the most proper plant according to the local weather condition.

Moving to the urban scale and considering the actual effects due to the presence of vegetation on the overall energy performance and on the outdoor air quality, soundscape and other related benefits, the increasing cost of the façade, estimated around the 70% (comprehensive of the structure, modules, plants and irrigation system) if compared to the same not vegetated envelope system, could be certainly balanced. A multidisciplinary approach should be thus followed and comprehensive investigations should be carried out.

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Acknowledgement

blinded

a **b**

Fig 1 Shredded felt for the substrate (a), VGMS pocket with plants (b)

a **b**

Fig 2 Plant species: *L. nitida* (a), *B. cordifolia* (b)

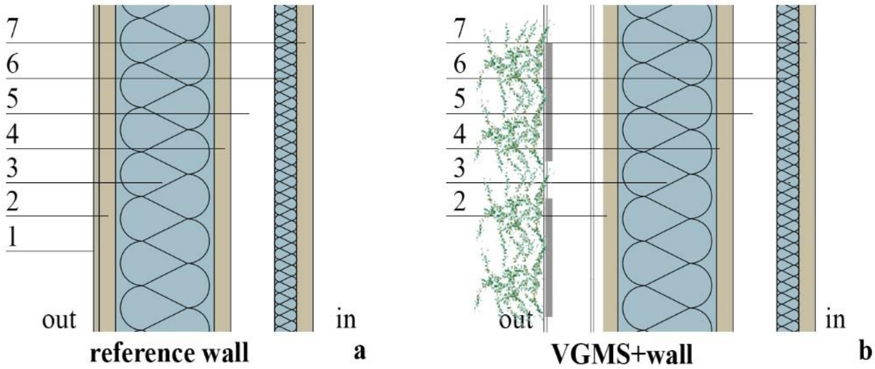

Fig 3 Test cell wall assembly. Reference wall (a) and Vertical Greenery Modular Systems + wall (b)

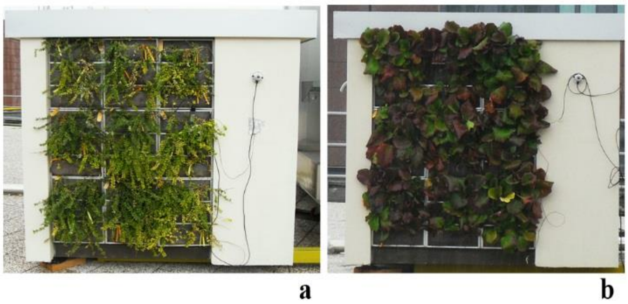

Fig 4 Test cell with *L. nitida* (a), *B. cordifolia* (b)

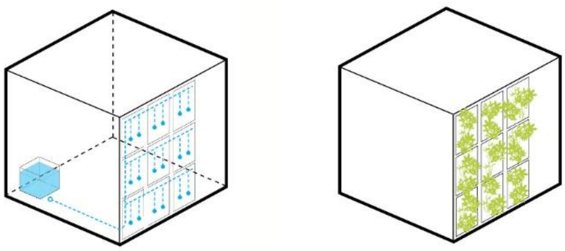

Fig 5 Schematic view of the test cells, irrigation system and green modules south facing

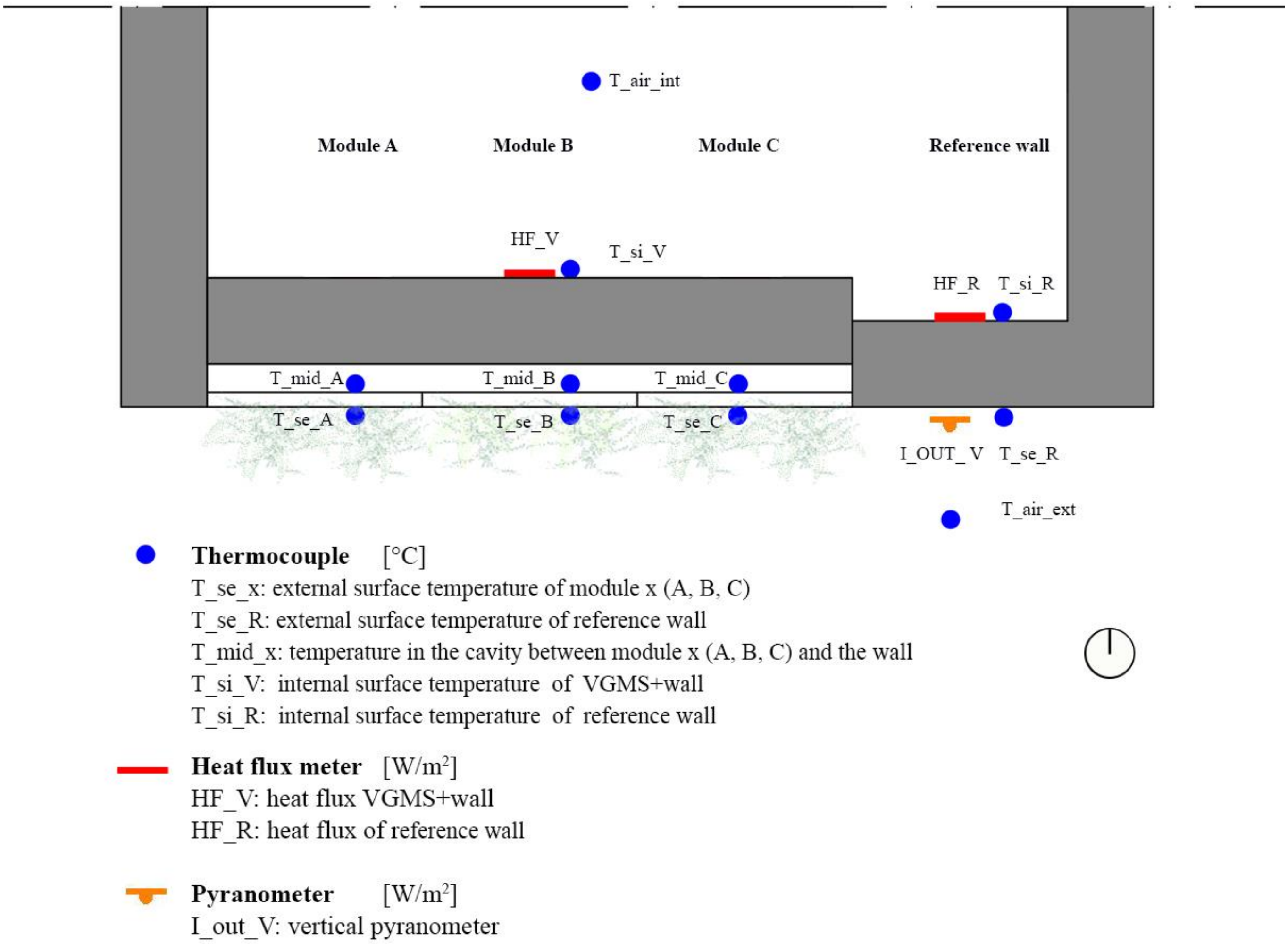

Fig 6 Schematic plan of the test cell with sensors position and names.

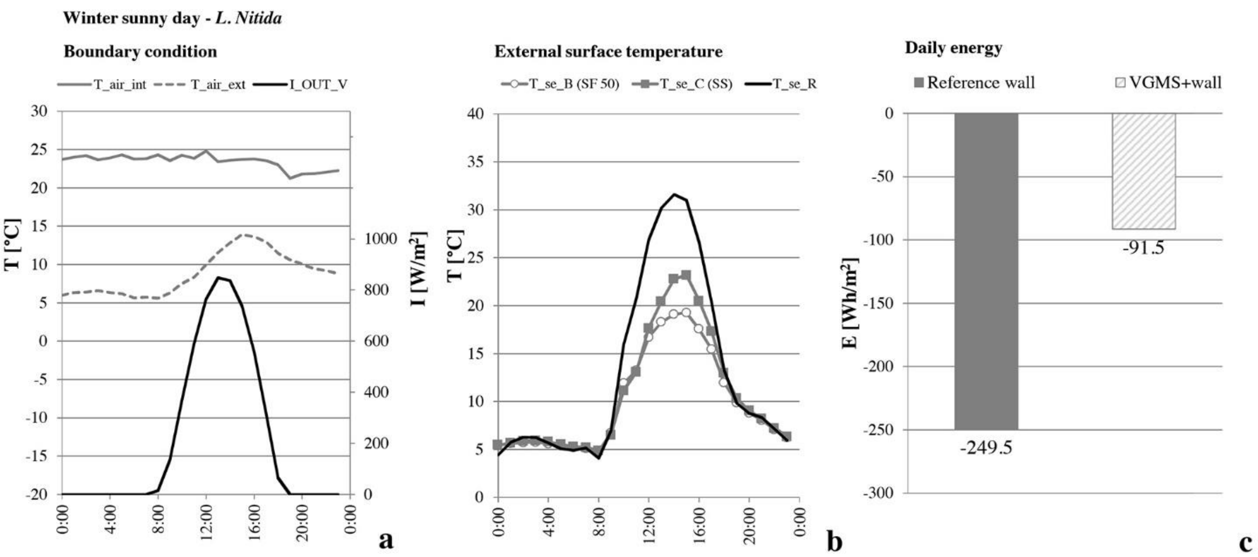

Fig 7 Boundary condition (a), surface temperature profiles of the reference wall and of the VGMSs (b), daily energy (c) *(*Typical winter sunny day - *L. nitida*)

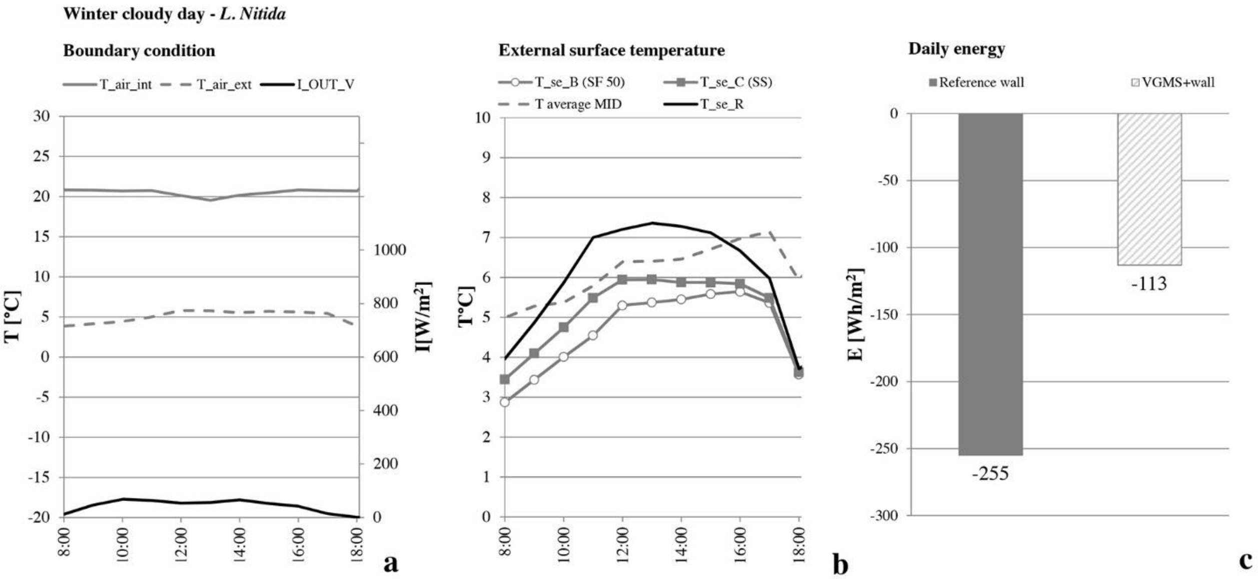

Fig 8 Boundary condition (a) and external surface temperature and middle layers of the three green modules (b), daily energy (c) *(*Typical winter cloudy day – *L. nitida)*

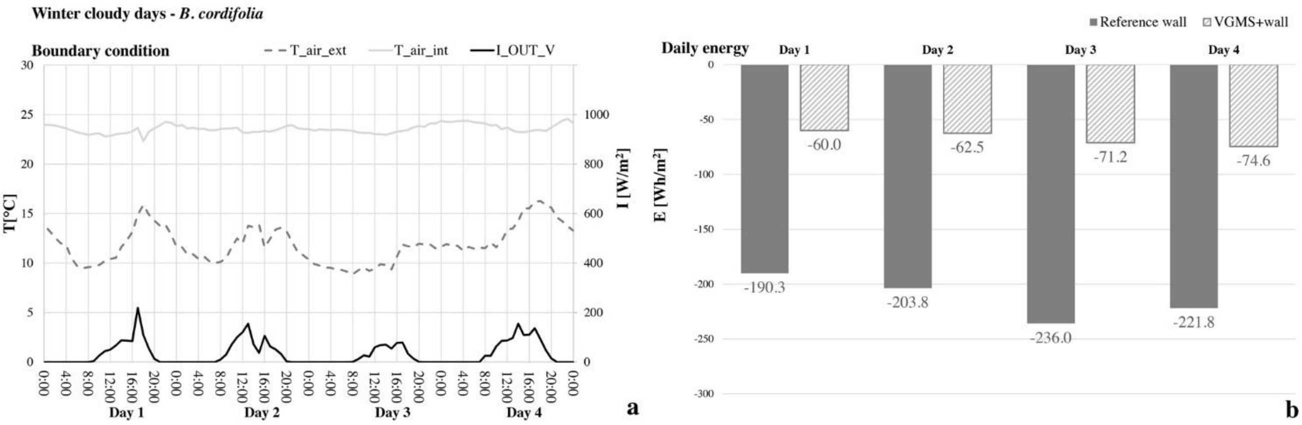

Fig 9 Boundary condition (a) Daily energy (Winter – *B.cordifolia*)

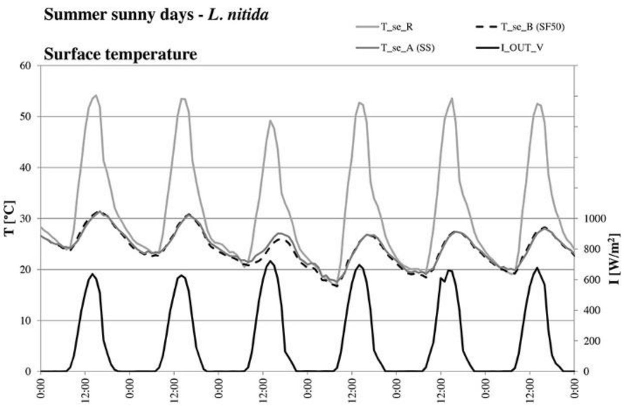

Fig 10 External surface temperature of the plastered wall and the green module (Summer – *L. nitida)*

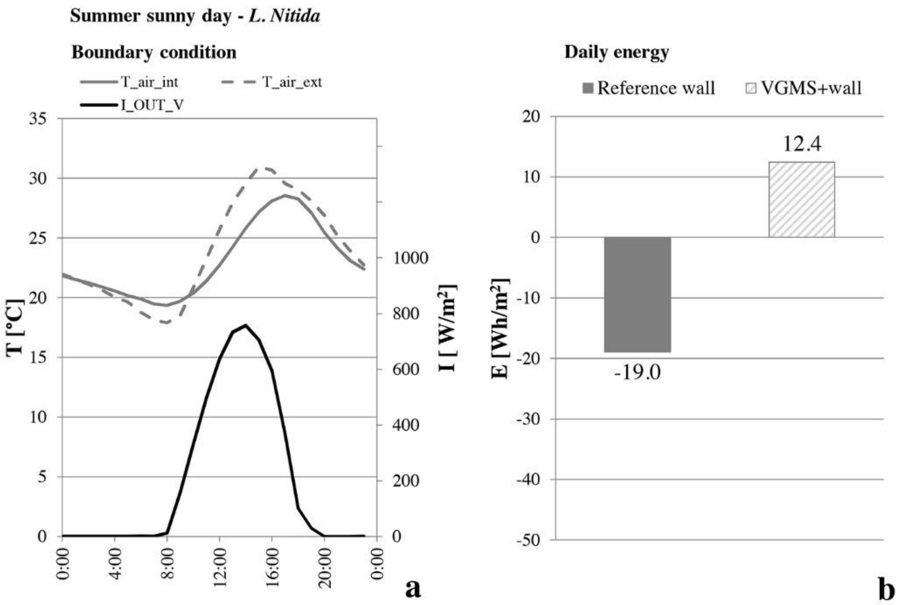

Fig 11 Boundary condition (a), daily energy (b) (Typical summer sunny day *L. nitida*)

Table 1. Wall layers and thickness (outer to inner layer)

Layers n°	**Layer name**	**Thickness** [m]
1	Plaster	0.005
2	Wood panel	0.015
3	Polystyrene insulation	0.090
4	Wood panel	0.015
5	Non ventilated air cavity	0.040
6	Polyester insulation	0.020
7	Wood panel	0.015

Table 2. Average plant dry weight and humidity ratio for *L. nitida* and *B. cordifolia*.

	L. nitida		*B. cordifolia*	
	SS	**SF50**	**SS**	**SF50**
Dry weight [g]	12.73	15.71	23.09	19.09
Humidity ratio [%]	64.9	64.4	73.2	72.8

Table 3. Effect of the two substrates (SS and SF50) on *L. nitida* and *B. cordifolia* leaves for one module 400 mm x 500 mm.

	L. nitida		*B. cordifolia*	
	SS	**SF50**	**SS**	**SF50**
L [n°]	3456	4720	134	140
LA [mm^2]	270x10^3	392x10^3	934x10^3	910x10^3
LAIm [-]	1.35	1.96	4.67	4.55

Table 4. Conductance (C*) and thermal transmittance (U*) values of VGMs and bare wall, *L. nitida* and *B. cordifolia.*

	Thermal conductance C* [W/m^{2}K]		**Thermal transmittance U* [W/m^{2}K]**	
	VGMs + wall	Bare wall	VGMs + wall	Bare wall
L. nitida	0.22	0.63	0.17	0.40
B. cordifolia	0.21	0.57	0.17	0.39