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Heat transfer reduction in building envelope with green façade system: a year-round balance in Mediterranean climate conditions

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Abstract

This study focuses on the thermal behaviour of a building prototype equipped with an evergreen green façade. The results of a two-year experimental campaign carried out under Mediterranean climate conditions are presented. Heat fluxes in the green covered wall and in the bare wall were analysed. Their comparison allowed finding out the energy saving, in terms of heat flux reduction through the wall, obtained through the use of the green façade. The energy benefit was evaluated throughout the year, differences between warm and cold periods and between times of day were pointed out. In the warm periods, energy saving was recorded mainly at daytime, while in the cold periods at night-time. The evergreen green façade allowed remarkable energy saving in wintertime as well. The monthly mean energy saving resulted equal to 8.19 MJ m^{-2}. The maximum benefit was achieved in July, 17.24 MJ m^{-2}, while the minimum in January, 2.33 MJ m^{-2}. The green façade provided an annual energy saving equal to 28.5% compared to the un-vegetated wall.

Keywords: building, nature-based system, sustainable urban development, passive design, energy saving, thermal screen, solar shading.

Nomenclature

AG	Air gap	HSR_{cum}	Cumulative solar radiation on the horizontal plane [MJ m^{-2}]
BW	Bare wall	LAI	Leaf area index
CP	Cool and cold period	LW	Living wall
CV	Convective heat transfer [W m^{-2}]	LWIR	Longwave infrared
CW	Covered wall	MS	Mean square
df	Degrees of freedom	P	P-value of the F statistic
E	Solar heat transfer [W m^{-2}]	R	LWIR heat transfer [W m^{-2}]
EAT	External air temperature [°C]	R_{tot}	Wall thermal resistance [K m^2 W^{-1}]
ERH	External air relative humidity [%]	$T_{ext\ sup}$	Wall external surface temperature [K]
ES	Energy saving [MJ m^{-2}]	$T_{int\ sup}$	Wall internal surface temperature [K]
F	F statistic	UGI	Urban green infrastructure
HF	Heat flux [W m^{-2}]	VGS	Vertical greenery system
GF	Green façade	W	Wind velocity [m s^{-1}]
GR	Green roof	WP	Warm and hot period
HSR	Solar radiation intensity on the horizontal plane [W m^{-2}]		

1 Introduction

Sustainable cities of the future require a process of urban environment reshaping, with the objective of achieving the sustainable transition, through improving the energy efficiency in buildings and using clean energy [1]. Government policies are important in promoting efficient building construction and retrofitting, thus favouring the environmentally sustainable change. The implementation of retrofitting interventions inside buildings could be hampered by the required reduction of the internal space. On the other hand, there are great opportunities to undertake work on the outside of the building envelope, such as on the rooftop or on the vertical walls.

Urban green infrastructures (UGIs) applied to the external envelope of buildings represent a great opportunity to achieve the aforementioned goals [2,3]. Firstly, UGIs allow to bring vegetation inside urban environment providing city-scale benefits , secondly these are a very promising passive sustainable technology for improving energy performance of new and existing buildings [4–8]. The application of UGIs is supported by the growing awareness of the need for greener and healthier cities.

Green roofs (GRs) and vertical greenery systems (VGSs) are among the forms of UGIs applied to buildings. At the building scale, these contribute to promote energy saving, greywater treatment, sound transmission reduction and envelope longevity. Through the protection and the shading of the building envelope, greenery systems are able to reduce building surface temperature in warm periods [9]. At the urban scale, when widely applied, GRs and VGSs can provide precious ecosystem services, contributing to urban heat island mitigation, biodiversity promotion, rainwater management, urban noise reduction and air quality improvement. Moreover, GRs and VGSs provide additional benefits concerning citizens' health and wellbeing [10]. Among the effects produced by greenery systems, the influence on the energy behavior of buildings deserves particular attention, given the high energy consumption of the building sector and its high environmental impact. Greenery systems can be an effective passive strategy for controlling heat transfer through the building envelope and reducing buildings energy demand for air conditioning [11–13]. Research efforts are needed to broaden the knowledge on the energy saving for cooling and heating achievable through greenery systems in order to better assess their actual benefit.

GRs mainly consist of roofs planted with different kind of vegetation and a growing medium. In developed cities, the roofs area accounts for about 40–50% of the total urban impermeable surface which can be turned green through GRs [14]. Roofs may have high inclination that complicates the construction of GRs or may be occupied by technological equipment serving the building itself reducing the surface available for GRs. An even greater possibility of application is given by VGSs due to the wider vertical surface of buildings in cities [4]. VGSs are characterized by plants grown directly on the wall or on supporting structures integrated into the vertical walls of buildings. VGSs comprehend two main classifications: green façades (GFs) and living walls (LWs). GFs can be implemented in the direct type or in the indirect or double skin form. Plants, which can be evergreen or deciduous, climbing or cascading, placed at the base of the façade or at different heights along it, are directly attached to the wall in the direct type and on a vertical support in the indirect type. In double skin GF the greenery is placed at a certain distance from the envelope, creating an air gap (AG) that influences the thermal performance of the system. LWs are characterized by a greater complexity than GFs, since they include supporting structure, plants, growing media and irrigation system. LWs can be continuous or modular. Continuous LWs are realized with a frame fixed to the wall and holding panels where plants grow. Modular LWs are composed of several interconnected elements, as vessels, planters, or flexible bags. Therefore, GFs can have a wider application than LWs, due to their simpler design, ease of installation and maintenance and to their lower cost [15,16]. When integrating vegetation on roofs and façades, some constraints and possible problems should be taken into account. Among these, the increased load of the building elements is particularly relevant from a structural point of view. The adopted solution should be compatible with the load-bearing capacity of the building and, for example, if only lightweight interventions are allowed. A problem may also arise from the concentration of water, vapour and roots in the greenery system. In this case, an accurate design of the adopted technology is the key-solution. A vapour barrier, a waterproof membrane, a root barrier and an adequate system for water collection and discharge must be provided. Choosing a system detached from the building envelope, as the double-skin GF, can also be an appropriate solution. This type of greenery system allows also to reduce the possible damage of the building's external surfaces caused by vegetation.

To date, a great deal of research is available on the impact of greenery systems at urban and building scales. However, most of this refer to GRs rather than to VGSs despite the wider applicability of the latter [17]. The main effects observed in the studies on the VGSs relate to shading, wind speed mitigation, plant evapotranspiration and increased envelope thermal insulation. Moreover, when an AG is created behind vegetation, the effects are greater [18–20]. In warm periods, the shading effect is particularly remarkable [21–23]. Evapotranspiration is a peculiar aspect of greenery systems that improves their cooling performance [24]. The benefits come from air and wall surface temperature reduction and in turn from the reduced energy demand for cooling [25–27]. During cold periods, the thermal and wind barrier provided by greenery are the most significant advantages [28–30]. The reduction in solar gain due to greenery could not be a significant factor in reducing energy efficiency in winter [31,32].

One of the most relevant issues related to the traditional building façades concerns their poor thermal performance and high thermal transmissivity, which in turn result in the poor energy efficiency of buildings.

Unlike traditional solutions, the current concept of building envelope has evolved towards a more complex system able to modulate and optimize the interaction between the indoor and outdoor environment. Thus, buildings' retrofitting can play a relevant role in achieving efficiency given the significant predominance of old buildings with traditional façades. The available technical solutions aim to minimizing energy need, adapting to climate conditions and promoting sustainability. Applicable solutions include: the addition of an insulation layer on the façade, the implementation of a double-skin glazed or an opaque ventilated façade, the use of specific finish coating or new adaptive and responsive materials. The application of greenery systems on façades is also among these solutions. VGSs are really living technologies making the building envelope like a living component able to adapt to the ambient conditions and in turn to improve energy performance, providing also the other aforementioned benefits.

Concerning the energy saving provided by the application of VGSs on buildings, many authors tried to evaluate this (Table 1). Wong and Baldwin [33] carried out numerical studies related to GFs. They evaluated the energy saving obtained with deciduous double skin GFs during the warm season in Hong Kong, under humid subtropical climatic conditions (Cfa - Köppen-Geiger classification [34]). They evaluated the heat exchanged by the building fabric with a total solar resistance including that of the GF, for fixed values of indoor and outdoor air temperature. They recorded a reduction of the energy demand for cooling equal to 76%, in comparison to the bare wall case. Cameron et al. [32] studied the energy performance of cuboids with evergreen direct GFs at the University of Reading, England (Cfb - Köppen-Geiger classification), during two particularly cold winters. They analysed the heaters power consumption and reported an energy saving for heating ranging between 21% (early winter) and 37% (late and colder winter). Regarding LWs, Pulselli et al. [35] simulated the energy performance of a building with greenery on a south oriented façade in hot summer Mediterranean climate (Csa - Köppen-Geiger classification). They used the EnergyPlus software and neglected the evapotranspiration effect. They recorded an energy saving for cooling and substantially no difference for heating. Perini et al. [36] monitored a LW system, made with different plant species, installed on the south wall of an office building in Genoa, Italy, charecterized by a Mediterranean climate (Csa - Köppen-Geiger classification). By evaluating the thermal energy exchanges in presence and in absence of the LW in a summer period (from May to September), they estimated a potential reduction of the cooling load by 26% in the case of the LW. The energy behaviour of a building equipped with a LW, in the Chinese cities of Hong Kong (warm temperature with hot summer periods and dry winter periods; Cfa - Köppen-Geiger classification) and Wuhan (warm temperature climate with hot summer and fully humid precipitation; Cfa - Köppen-Geiger classification), was simulated through EnergyPlus by Dahanayake and Chow [37]. Their results suggested a slight decrease in the cooling energy demand, equal to 3%, while a disadvantage in cool periods with an increase in the energy demand for heating, due to the presence of the LW. An experimental study was conducted by Djedjig et al. [38] on scaled-down buildings with west exposed LWs in La Rochelle, France, under Oceanic climate conditions (Cfb - Köppen-Geiger classification). By analysing the heat flux measured through heat flux sensors at the green and bare walls, they found out a 67% reduction of the cooling energy consumption in summer and 20% reduction of the heating energy consumption in winter, in presence of the LW. The analyses were developed on experimental data of a summer month (August) and of a winter month (December). Coma et al. [39] carried out an experimental study by applying indirect deciduous GFs and evergreen LWs on test rooms during a few days of a cooling (June-July) and a heating (December-February) period, under Mediterranean climatic conditions (Csa - Köppen-Geiger classification). The authors analysed the electrical energy consumption of the heat pumps used for heating and cooling. Their results showed a significant energy saving during the warm period for both the GFs and the LWs. No extra energy consumption for the GFs and a slight energy saving for the LWs were recorded in the cold period.

Table 1. Significant previous studies on the use of VGSs for energy saving in buildings.

Ref.	VGS type	Location/Country	Climate	Type of study	Period	Parameters	Findings
[32]	evergreen direct GF	Reading, UK	Marine west coast (Cfb)	experimental	two cold winters (January-March, December-March)	heaters power consumption of planted cuboids	heating energy demand reduction between 21% and 37%
[33]	deciduous double skin GF	Honk Kong, China	Humid subtropical (Cfa)	numerical	warm season	heat exchanges through the building's fabric	reduction of cooling energy demand of 76%
[35]	LW	Siena, Italy	Mediterranean (Csa)	simulation	- cooling season - heating season	building energy consumptions	- cooling energy demand reduction up to 2.07E+09 J yr^{-1} - no difference for heating energy demand
[36]	LW	Genoa, Italy	Mediterranean (Csa)	experimental	summer period (May-September)	thermal energy exchanges between indoor and fresh air	potential cooling load reduction of about 26%
[37]	LW	Hong Kong and Wuhan, China	Humid subtropical (Cfa)	simulation	- cooling period - heating period	building energy consumptions	- decrease in cooling energy demand of 3% - increase in heating energy demand
[38]	LW	La Rochelle, France	Oceanic (Cfb)	experimental	- a summer month (August) - a winter month (December)	measurements of the heat fluxes	- reduction of cooling energy demand of 67% - reduction of heating energy demand of 20%
[39]	- deciduous double skin GF - evergreen LW	Puigverd de Lleida, Catalonia, Spain	Mediterranean (Csa)	experimental	- cooling period (June-July) - heating period (December-February)	electrical energy consumption of heat pumps	- significant energy saving in warm period by GF - significant energy saving in warm period by LW - no extra energy consumption for GF in cold period - slight energy saving for LW in cold period

Upstream of the present study is the awareness, highlighted by the literature review, that many lacks and limitations still exist in research concerning the energy performance of evergreen GFs. The literature review showed that most of the studies on VGSs energy performance deal with LWs, although GFs can be a more attractive solution due to their easier and cheaper construction and management. The few available studies on GFs energy performance refer to different climatic conditions and different approaches (experimental and numerical) for achieving the results. This makes it very difficult to compare the respective findings. Further studies are needed to assess the energy performance in the different climatic areas. Research has mainly focused on the summer season. Studies should further investigate the GFs energy performance also in the cold periods and evaluate the possibile increase in winter heating demand. In case of increased heating demand, experimental tests should assess if this increase is offset by the reduced cooling demand obtained in summer [4,40]. In particular, as highlighetd by Koch et al. [41], while few research findings are available on the energy saving for cooling, none concerns the energy saving for heating provided by double skin GFs. Moreover, studies on the energy saving evaluation based on long-term experimental observations are still lacking [4,40]. The experimental period should cover at least one year without interruptions. The thermal performance of buildings equipped with a green envelope is strongly influenced by the plant type and by its leaf density to which the leaf area index (LAI) is closely connected [42]. Even perennials, in comparison with deciduous ones, have growth patterns that confer a dynamic behaviour throughout the year to the green layer, which therefore has variable LAI values, depending on the weather conditions. Consequently, the experimental research should be extended to obtain significant results taking into account this biological dynamics of perennials throughout the year.

Still existing research gaps mainly relate to the shortage of studies supported by long-term experimental data on the year-round energy performance of evergreen double skin GF.

These considerations are the starting point of our study and underline its need and novelty. Our study concerns the analysis of the energy behaviour of a building prototype equipped with an evergreen double skin GF, under Mediterranean climatic conditions (Cfa - Köppen-Geiger classification). The main novelty of the present research consists of the evaluation of the practical potentials of an evergreen GF thanks to the support of multi-year experimental data. We studied how the presence of the plants affected the overall heat transfer through the external surface of the wall behind vegetation and this was compared with the case of the bare wall. Through our applied research, we tried to answer the basic question: “Does the application of an evergreen indirect GF provide a year-round energy advantage?”

The main contributions of our study to the enrichment of the scientific knowledge include the energy analysis focused on the specific typology of the double skin GF and the evaluation of the energy performance in summer, winter and intermediate seasons, daytime and night-time, based on long-term (two years) experimental data.. The energy saving provided by the evergreen GF was evaluated using as parameter the reduction in wall heat transfer. This was defined as the reduction of the cumulative overall heat transfer through the external surface of the covered wall (CW), behind the vegetation of the GF, compared with that through the bare wall (BW). Analyses were performed for different climate seasons, daytime and night-time. Up to now, research has mainly evaluated energy consumption of equipment for heating and cooling in presence and absence of vegetation. We refer to the heat transfer reduction as energy saving because of the strong connection between the envelope performance and the energy need of the building.

2 Materials and methods

A multi-year experimental campaign has been conducted at the experimental centre of the University of Bari with the aim of testing the energy behaviour of a GF. The experimental site is located in Valenzano, Italy (latitude 41.0199° N, longitude 16.9048° E, elevation 124 m a.s.l.). Its climate is typically Mediterranean, mild temperate characterized by hot and humid summer; it is classified in the Cfa category, as defined by Köppen-Geiger [34].

The experimental GF prototype has a rectangular plan with dimensions of 4.20 m x 1.50 m and a height of 2.00 m (Figure 1). The wall covered with vegetation was south oriented. It has no thermal insulation and was made of hollow bricks, placed with horizontal holes, held together with cement mortar and externally finished with a layer of white plaster. The masonry of hollow bricks has a thickness of 0.20 m and a thermal conductivity of 0.235 W K^{-1} m^{-1}, the external plaster has a thickness of 0.01 m and a thermal conductivity of 0.54 W K^{-1} m^{-1}. The total wall thickness is 0.21 m, and the overall thermal resistance is 0.87 K m^2 W^{-1}. This wall was built to simulate an exterior wall of a building according to the construction methods widespread in the Mediterranean area, in relation to the recent building heritage. The objective of this research was to evaluate the use of a GF as a nature-based solution for improving the thermal performance of an existing wall that has a high thermal transmittance and no thermal insulation layer.

The south wall was divided into a bare part and a GF part to study the thermal behaviour of the GF and to compare it with a BW. To thermally separate the CW part from the BW, embedded panels of extruded polystyrene were interposed perpendicular to the wall plane (Figure 1). The GFs were indirect, 0.15 m away from the wall. The green layer was made up of plants of an evergreen climbing species, the *Rhyncospermum jasminoides*, supported in their upward growth by an iron net.

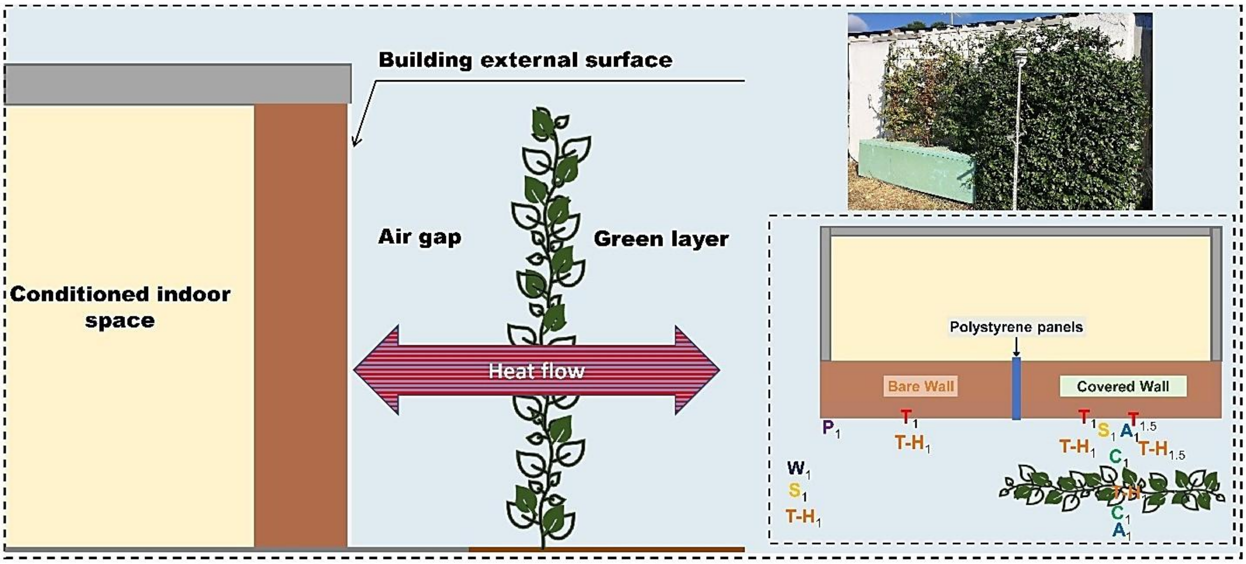


Figure 1. Green façade system: vertical section identifying layers; horizontal section describing sensors types and positions (A= ultrasonic anemometer; C= radiometer; P= pyrgeometer; S= pyranometer; T-H= temperature/RH sensor; T= thermistor; W= anemometer; pedices 1/1.5= sensor at a height of 1 m/1.5 m).

Three data loggers (two CR10X and one CR1000 Campbell, Logan, USA) and many sensors constitute the measurement system (Figure 1). The data loggers recorded the 15-minute average value of the measurements taken every minute. The sensors were placed in the center of the walls to avoid the influence of the border effects on the measured data. Solar irradiation on a horizontal plane, in the wavelength range 0.3-3 mm, was measured by using a pyranometer having an accuracy of 10 W m^{-2} (model 8-48, Eppley Laboratory, Newport, RI, USA). A Wind Sentry anemometer (model 03002, R.M. Young Company, USA) was used to detect wind speed and direction with an accuracy of 0.5 m s^{-1} and of ± 5°, respectively. Indoor and outdoor air temperature and relative humidity were measured through HygroClip-S3 sensors (Rotronic, Zurich, Switzerland) with an accuracy of ± 0.1 °C and ± 0.8%, respectively. Wall surface temperature was measured by thermistors having an accuracy of ± 0.15 °C (Tecno.el s.r.l. Formello, Rome, Italy); these were placed on the internal and external surfaces of the walls. Canopy temperature was measured by means of Apogee SI 400 radiometers (Logan, UT, USA) with an accuracy of 0.2 °C. To measure incoming long-wave infrared (LWIR) radiation on the wall a PIR pyrgeometer (Eppley Laboratory, Newport, RI, USA), having a sensitivity of 4.18 μV/W m^{-2}, was used. A pyranometer PIR02 (Geoves s.n.c., Conegliano, Italy), with a sensitivity of 10 μV/W m^{-2}, detected solar radiation behind the vegetation. Air speed and direction in front of and behind vegetation were measured, with an accuracy of 0.3 m s^{-1} and of ± 1°, respectively, by means of ultrasonic anemometers (ATMOS 22, METER Group, Inc., Pullman, WA, USA).

The prototype internal air was conditioned in both warm and cold periods. A portable monoblock heat pump air conditioner (Ellisse hp, Olimpia Splendid, Cellatica, Italy) was used in summer. A fan heater (CH 7000 TURBO Aspira, Fantini Cosmi, Milan, Italy) was used in winter. The indoor air temperature was managed for both heating and cooling by means of a room chronothermostat (C804, Fantini Cosmi, Milan, Italy). The temperature set point was 20 °C and 26 °C, in the cold and warm season, respectively.

Data were collected from April 2019 to March 2021. This period was characterized by a maximum and a minimum value of monthly cumulative solar radiation on the horizontal plane (HSR_{cum}) equal to 788.6 MJ m^{-2} and 136.0 MJ m^{-2}, respectively. The highest and lowest recorded values of external air temperature (EAT) were 38.4 °C and -0.4 °C, respectively, the mean air relative humidity (ERH) was equal to 69.6% and the minimum to 14.9% and the maximum wind velocity (W) was 18.4 m s^{-1}. The maximum and minimum values of the monthly HSR_{cum} were recorded in July 2020 and in December 2019, respectively. EAT maximum and minimum values were recorded in June 2019 and in March 2020, respectively. The lowest value of ERH was recorded in July 2019. W maximum was recorded in April 2019. The thermal performance of the GF was investigated throughout the year, both in the heating and cooling periods, with the aim of finding out the energy advantage provided by the GF. Daytime and night-time performances were analysed and compared, as well. Daytime hours were considered as those when solar radiation on the horizontal plane was greater than zero.

The overall heat transfer at the external surface of the BW and of the CW was evaluated by taking into account solar (E), LWIR (R) radiative and convective (CV) heat fluxes according to Convertino et al. [19], [28]. Cumulated values were considered for analysing the heat flux reduction through the wall obtained with the GF. The overall heat fluxes (HF, W m^{-2}) through the BW (HF_{BW}) and CW(HF_{CW}), which represent energy input or output for the building, were calculated by Eqs. (1)–(2). HF terms include both the conductive heat transfer and the heat storage.

$$HF_{BW} = E_{i,BW} - E_{o,BW} + R_{i,BW} - R_{i,BW} + CV_{EA,BW} \tag{1}$$

$$HF_{CW} = E_{i,CW} - E_{o,CW} + R_{i,CW} - R_{i,CW} + CV_{AG,CW} \tag{2}$$

where $E_{i,BW}$, $E_{o,BW}$, $E_{i,CW}$, $E_{i,CW}$ [W m^{-2}] are the solar radiative energy input and output at the BW and CW, respectively, and $CV_{EA,BW}$ and $CV_{AG,CW}$ [W m^{-2}] are the convective energy transfer between the external air (EA) and the BW and between the AG and the CW, respectively.

Warm and hot (WP) and cool and cold (CP) periods were considered. These were defined based on 10-day average EAT values and on a base temperature equal to 18 °C. The threshold value of 18 °C was chosen considering the baseline temperature for defining the heating/cooling degree days. According to Tsikaloudaki et al. [43], this value was selected for both heating and cooling in order to cover all European geographical areas and to take into account ASHRAE recommendations [44–46]. Considering this base temperature and the 10 days mean EAT values, we managed to define in detail WPs and CPs. WPs were identified as periods with the mean EAT higher than 18 °C, i.e. periods in which reduced thermal gains were desired. CPs were defined as periods with the mean EAT lower or equal to this temperature value, i.e. periods in which reduced thermal losses were desired.

The air conditioning system kept the average internal air temperature at 20.4 °C in the CP and at 23.2 °C in the WP. As for the cooling system, this managed to keep the mean indoor air temperature below the set-point value of 26 °C even in very hot days. For example, during a critical August week characterized by a maximum daily outdoor temperature of 38.2 °C, the recorded mean indoor temperature was 25.7 °C.

In this study, the energy saving (ES) was not regarded as reduction of energy consumption for heating/cooling of the air conditioning system. It was evaluated in terms of thermal energy transfer through the external surface of the envelope, by taking into account the outdoor climate conditions. The aim of the research was to compare the energy transfer in a vegetated and a bare wall of the same room, both south oriented. Depending on whether it was a WP or a CP, we evaluated if the energy gains/losses were desired at that time and thus if these were an ES or not.The ES provided by the GF was defined as the difference between the overall heat transfer through the external surface of the two walls. It was assumed a threshold value of 18 °C for the EAT. When EAT was higher than 18 °C (WP weather condition), the GF recorded an ES when the incoming energy flow in the CW was lower than that through the BW. When EAT was lower than 18 °C (CP weather condition), the GF provided ES when the outgoing energy flow in the CW was lower than that through the BW.

3 Results and discussion

The analysis of the overall heat transfer through the CW and the BW was performed using two years data. Heat transfer varied over the months of the year along with the microclimate and surfaces parameters, which caused such changes in energy transfer. As shown in Figure 2, the physical conditions of the CW differed from those of the BW since the former were altered by the presence of the vegetation. Concerning the external surface temperature, it was observed that the amplitude of oscillation of the curve was lower for the CW than for the BW, both in CP (Figure 2(a)) and in WP (Figure 2(c)). The external surface of the CW was generally colder than that of the BW at daytime and warmer at night-time. Regarding the nearby air, the temperature in the AG was generally higher than that in proximity of the BW during CP; this difference was more evident at daytime than at night-time (Figure 2 (a)). In WP, the air behind the vegetation was generally colder during the day and warmer during the night (Figure 2(c)). Solar radiation hitting the external surface of the CW was significantly reduced in comparison with the BW, both in CP (Figure 2(b)) and in WP (Figure 2(d)). The air velocity in the AG was also generally reduced by the presence of vegetation (Figures 2(b), 2(d)).

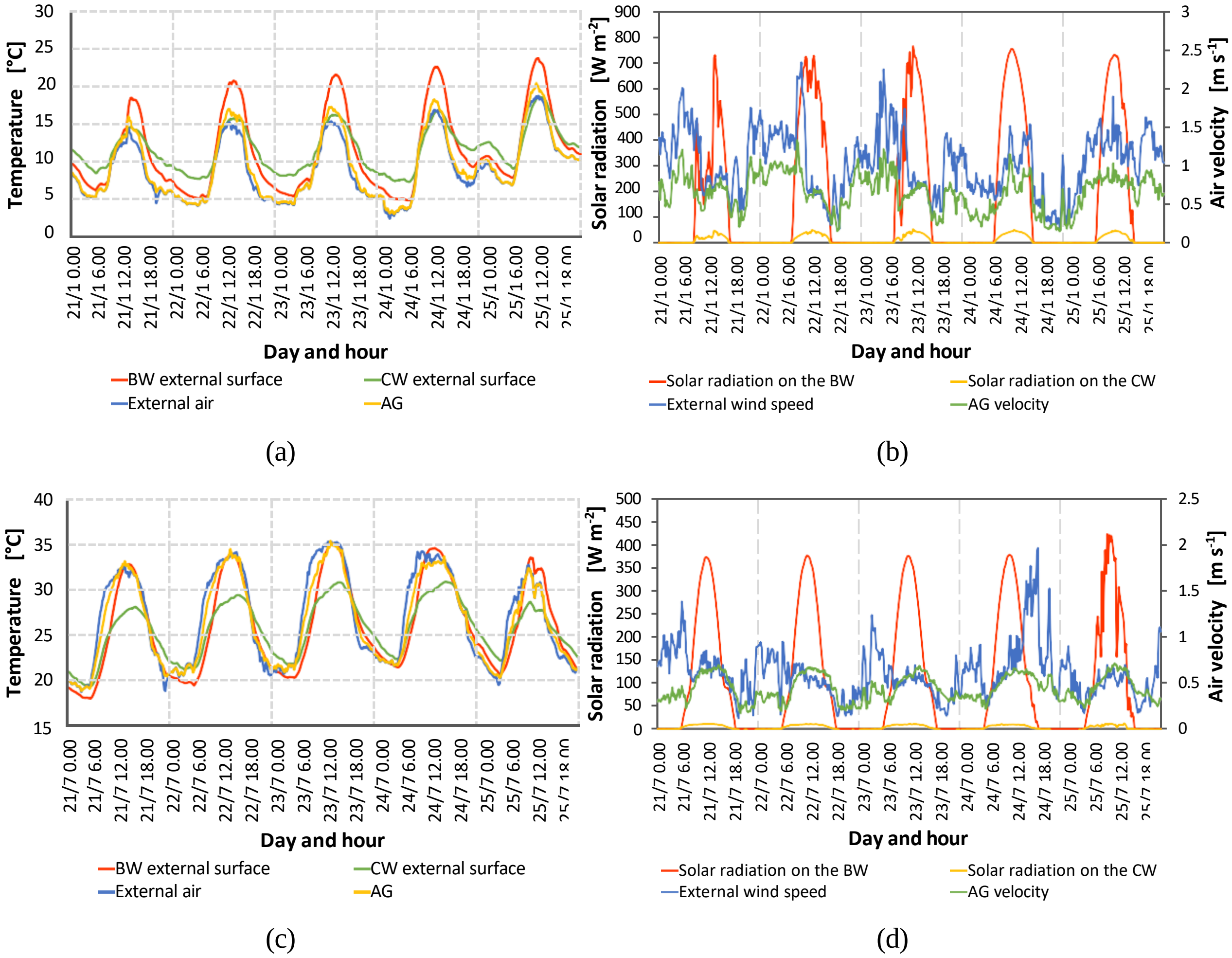


Figure 2. Air and surface temperature during cold (a) and warm (c) days; solar radiation and air velocity during cold (b) and warm (d) days.

The alteration of the boundary conditions achieved through the GF system resulted in a variation of the heat transfer through the CW compared to the BW. This heat flux change was considered to quantify the advantages or disadvantages of applying the GF throughout the year.

The daily mean energy transfer through the two walls is shown in Figure 3 for each month, together with the mean monthly EAT. Negative values of the energy transfer stand for energy output for the surface, positive values stand for energy input. Figure 3 shows that, in general, as the mean monthly EAT decreases, the energy losses increase. Energy was lost during most months of the year for both walls. The maximum energy loss was recorded in January for both the BW (2.23 MJ m^{-2}) and the CW (2.15 MJ m^{-2}). Energy gain was recorded only for the BW in May and June. In cold months, with lower EAT, characterized by less sunlight hours and lower solar irradiance than the warm months, the thermal behaviour of the walls was mostly influenced by the convective and long-wave radiative transfer rather than by the solar irradiation. Although the GF limited daytime solar gains, it allowed for reduced energy losses. The GF acted as a thermal barrier by limiting the convective and long-wave radiative losses (Figure 4). The reduction in convective and long-wave radiative losses at night was higher than the decrease in solar gain at daytime. In warmer months, with higher EAT and solar irradiance, instead, the shading effect strongly reduced the solar gain of the CW (Figure 4). This was not offset by the reduction of heat losses due to the thermal barrier effect provided by the GF at night-time.

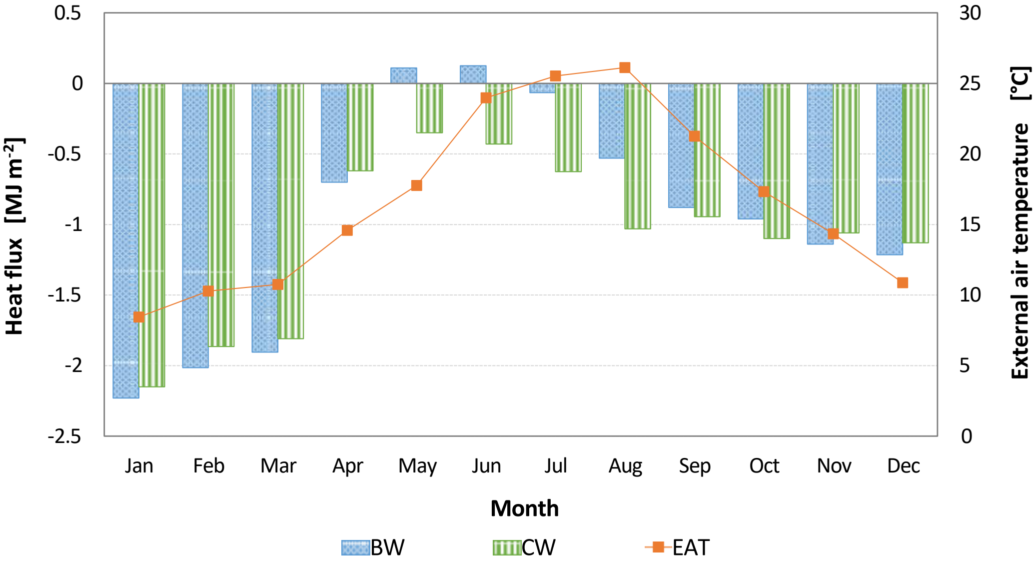
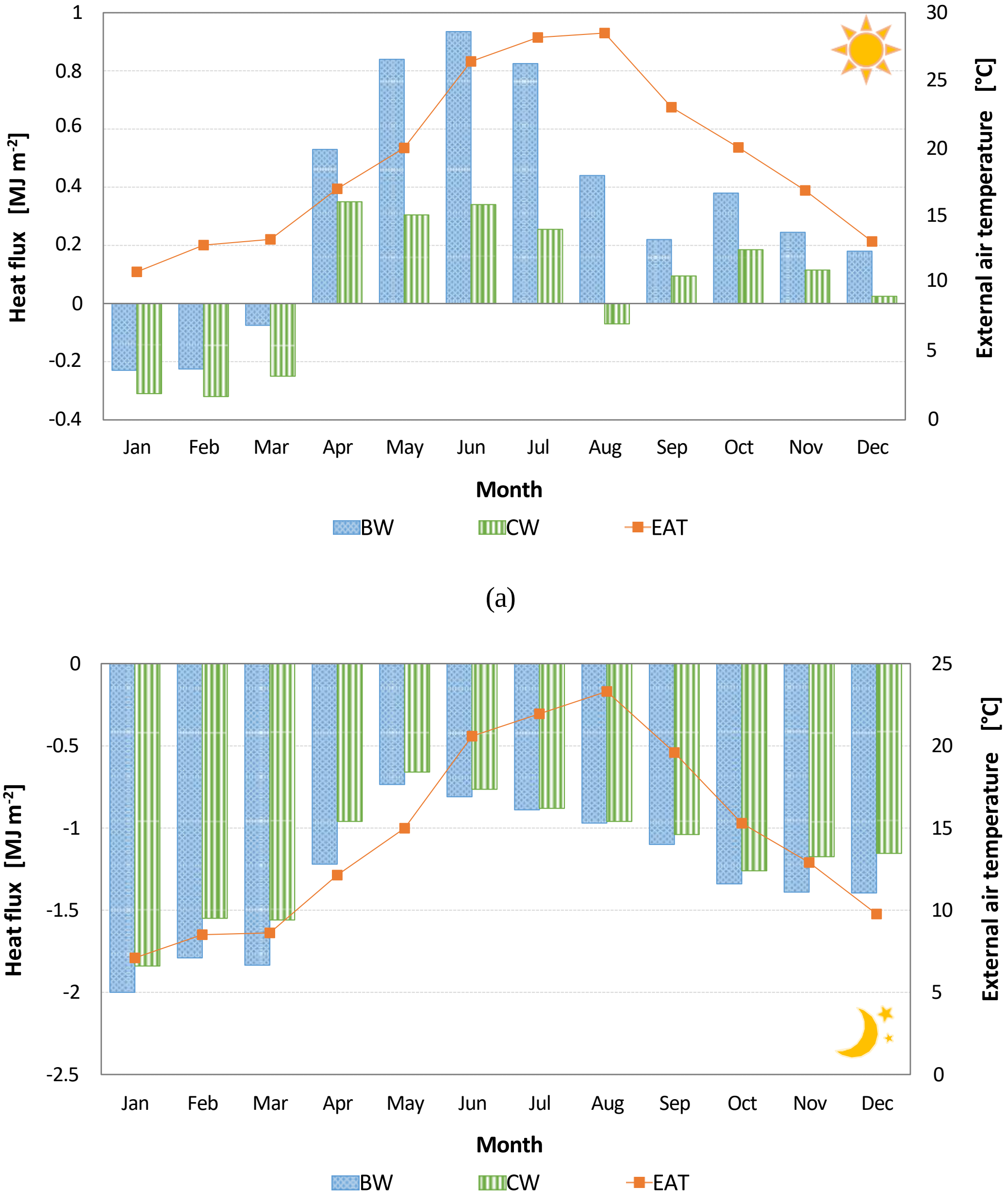


Figure 3. Daily mean of the cumulative energy transfer through the bare and covered wall (primary axis), and average external air temperature (secondary axis).

During daytime, the CW always recorded higher energy losses and lower energy gains compared to the BW (Figure 4(a)). The BW and the CW started to record energy gains when EAT was higher than 13.2 °C. The maximum daily mean energy gain for both the BW (0.94 MJ m^{-2}) and the CW (0.34 MJ m^{-2}) was recorded in June. The highest energy loss was recorded in January for the BW (0.23 MJ m^{-2}) and in February for the CW (0.32 MJ m^{-2}).

At night-time, energy losses were obtained in all the months (Figure 4(b)). The daily mean energy losses from the BW were always higher than those from the CW. The lowest losses for both the CW (0.74 MJ m^{-2}) and the BW (0.66 MJ m^{-2}) occurred in May, with a monthly mean night-time EAT equal to 15.0 °C. The highest daily mean losses for the BW (2.00 MJ m^{-2}) and for the CW (1.84 MJ m^{-2}) occurred in January, when the mean EAT was the lowest (7.1 °C).



(a)

(b)

Figure 4. Daily mean of cumulative energy transfer through the bare and covered wall (primary axis) and mean external air temperature (secondary axis), at daytime (a) and night-time (b).

The ES provided by the CW was evaluated as the reduction of the incoming energy in WPs and of the outgoing energy in the CPs. It was observed that the GF allowed to pursue ES in each month of the year (Figure

5). The mean value of the ES was equal to 8.19 MJ m^{-2} per month, while the annual value was 98.27 MJ m^{-2}, i.e. 28.5% of the total annual flow through the BW. The maximum ES was achieved in July, the minimum in January.

Overall, the highest advantage was obtained in warmer months, when a high daily ES and a very low night-time energy penalty were recorded (Figure 6). The ES provided by the GF in each winter month suggested that the negative effect of reduced solar heat gain was less than the night-time benefits, likely due to the longer duration of nights in winter. Interestingly, there were also months in which the ES was provided by the GF both during daytime and night-time (Figure 6). These are months (May, September, October) that can be considered "of transition" from cool to warm period and vice versa. In these months ES was obtained all day long, thanks to the daytime shading and evapotranspiration, and thanks to the night-time thermal barrier effect. Moreover, these intermediate months were characterized by the change in temperature and oscillation around the threshold value of 18 °C. Thus, it happened that in the same month ES was achieved partly by reducing energy losses and partly by increasing them. This result was affected by the specific climatic conditions (air temperature, intensity and inclination of solar irradiance) characterizing the experimental Mediterranean site.

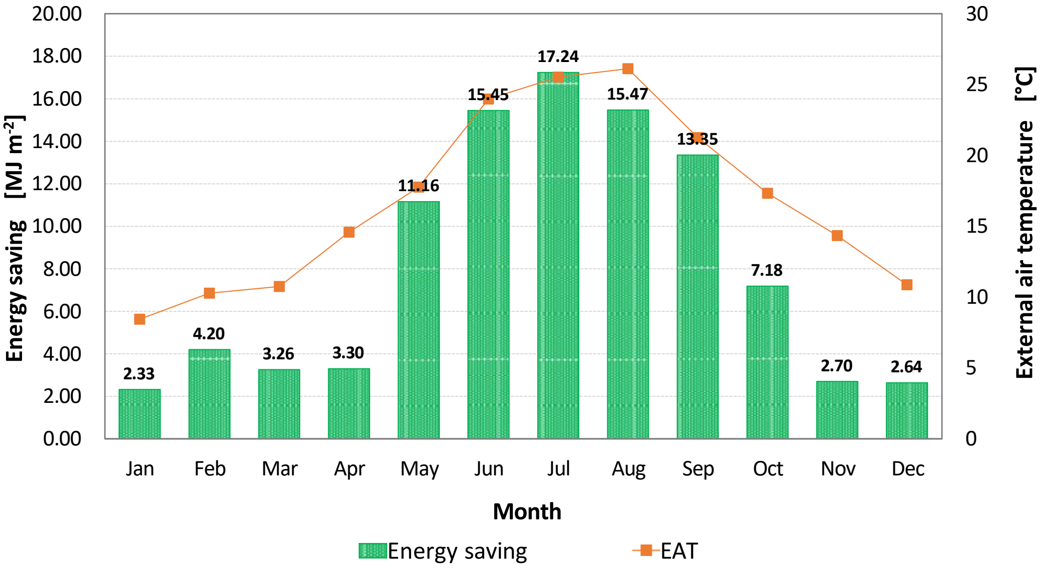
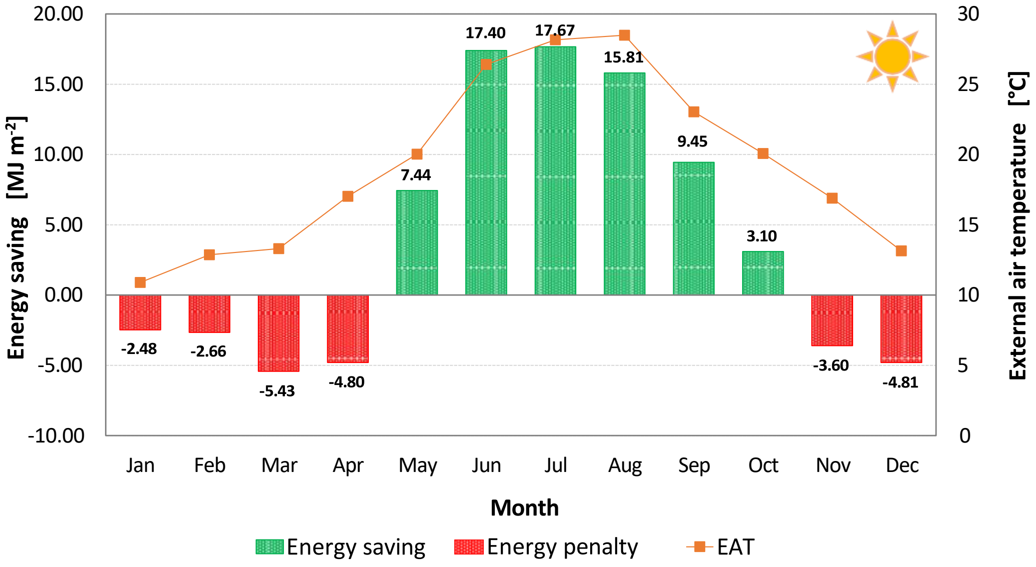


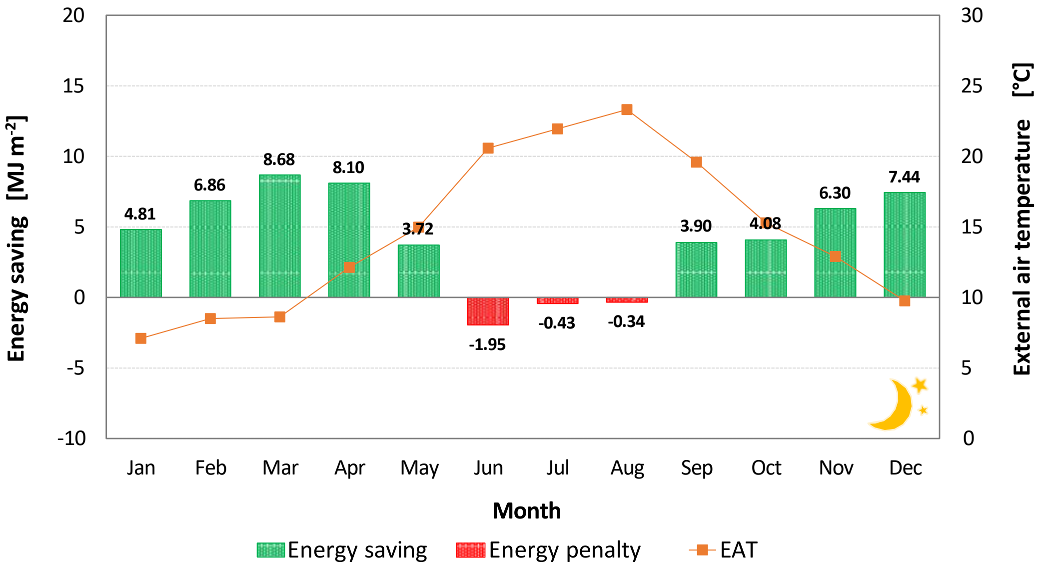
Figure 5. Monthly mean energy saving, as heat flux reduction, provided by the green façade (primary axis) and monthly mean external air temperature (secondary axis).

During daytime, the GF was able to provide ES except for the coldest months of the year, when EAT was below 16.9 °C (Figure 6(a)). The maximum benefit was achieved in July, while the highest energy penalty occurred in March. Overall, the yearly daytime ES amounted to 47.10 MJ m^{-2}. This was equal to 37.8% of the total annual flow through the BW, at daytime.

At night-time, ES was recorded with the exception of the hottest months (Figure 6(b)). The highest value was obtained in March, while the highest energy penalty occurred in June. During the night-time of the winter months, the GF lowered energy losses through CW compared to BW. This could be attributed both to the GF's ability to hinder the escape of long-wave radiation to the outside environment, as well as to act as a wind-barrier capable of lowering the wind speed and thus reducing convective heat losses. The total annual night-time ES was equal to 51.17 MJ m^{-2}. This was equal to 10.9% of the total annual flow through the BW, at night-time.



(a)



(b)

Figure 6. Monthly mean energy saving, as heat flux reduction, provided by the green façade (primary axis) and mean external air temperature (secondary axis) at daytime (a) and night-time (b).

To assess the energy saving provided by VGSs, most of the authors evaluated heating and cooling energy consumption, while we studied the overall heat transfer through the external surface of the wall. The building energy consumption for heating and/or for cooling is strictly related to the thermal performance of the envelope. Thus, the assessed energy saving provided by the GF in terms of thermal energy benefits can be qualitatively compared to the results found in the literature and was found to be consistent with these. Our findings on the annual benefit are consistent with the results of Djedjig et al. [47], who found an annual energy saving provided by green wall up to 37%. In detail, they obtained a cooling load decrease from 7.8 kWh m^{-2} to 2.5 kWh m^{-2} in La Rochelle and from 17.6 kWh m^{-2} to 7.4 kWh m^{-2} in Casablanca, while no remarkable energy saving and even a slight increase in the heating load for the building in Casablanca.

Our findings suggest an improvement in summer envelope performance and in turn that GF is an effective passive system for reducing cooling energy demand. Consistently, Djedjig et al. [48] found that the cooling demand of the analysed vegetated buildings was up to 37% lower than that of unvegetated ones. Kontoleon and Eumorfopoulou [49] concluded that the daily cooling requirements of buildings with greenery were lower and ranged from 4.65% for the north-oriented wall to 20.08% for the west one. Perini et al. [36] found that vertical greening systems have a cooling capacity useful to reducing the cooling demand of buildings, with a theoretical energy saving potential of 26% in summer. In the study by Coma et al. [39] the green wall allowed to reach the highest energy saving during the cooling period, up to 58.9% if compared to the reference building and GF up to 33.8%. As found in our research, they too highlighted that the highest energy saving during summer was achieved at daytime, while after sunset the energy consumptions of the buildings with and without the vertical greening were more similar.

Our experiment pointed out that even in wintertime the GF improved the thermal behaviour of the envelope. Coma et al. [39] found a slight reduction in the heating energy demand for the evergreen green wall, especially at night. Xing et al. [30] found a heat flux reduction of 3.1 W m^{-2} through vegetated wall in comparison with a bare wall and an energy saving for heating equal to 18%. Reductions in heating energy consumption of 8.7% and 11.9% were also highlighted by Djedjig et al. [50] in the case of buildings with green walls.

4 Conclusions

Green façades, as a type of urban green infrastructure, can provide remarkable contributions to making our cities more sustainable, energy efficient and healthier.

This research focused on evaluating the energy advantages provided by a green façade compared to an un-vegetated wall. The main contributions of our study concern the quantification of the energy saving, as reduction in envelope heat flux, provided by the green façade. Energy saving was evaluated in terms of heat transfer reduction since the envelope performance is directly linked to the building’s energy consumption for air conditioning. Our findings are the result of a two-year experimental test. Data were collected on a green façade prototype realized with the evergreen species of *Rhyncospermum Jasminoides* on a south facing wall, under Mediterranean climatic conditions. Hence the novelty of the present study: the quantification of the energy saving potentials of an evergreen GF, that was tested in real conditions throughout two years.

Our findings highlighted the positive effect in terms of energy saving provided all year round by the green façade realized with an evergreen plant. A yearly energy saving of 98.27 MJ m^{-2} was obtained. In the warm months, energy saving was recorded at daytime, while energy penalty at night-time. In the cool months, the results were the opposite. Anyway, the negative effects in both warm and cold seasons were offset by the positive ones.

The findings of this study refer to the evaluation of the effects provided by the experimental GF with a single orientation, the south one. The south-oriented GF was chosen because the south exposed walls are those requiring high insulation/shading under Mediterranean climate conditions. The application of the GF on walls with other orientations could lead to different results.

Our research relies on the evaluation of the cumulative energy transfer values, but it does not pretend to dynamically describe the heat transfer through the wall.

As future development of this research, further study should be carried out in order to analyse walls characterized by other than the southern exposure. Moreover, this study is preparatory for elaborating an energy modelling tool to simulate the energy functioning of GFs by using software. This would make the evaluation of the energy behaviour of buildings with GFs easier and faster.

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