Chapter 10
Ventilative Cooling and Urban Vegetation

Katia Perini and Gabriel Pérez

Abstract The chapter analyses the potential usage of vegetation in cities to provide cooling effect due to plant evapotranspiration, shading and air flow control, discussing how lower temperatures, pressure differences and air flows can favour natural ventilation to improve comfort and reduce energy demand. Due to the urban heat island phenomenon, which is connected with the lack of green areas and the amount of surfaces with low albedo, cities face discomfort issues and higher energy demand for air conditioning. Urban greening, green roofs and vertical greening systems, depending on plant species, material used and climate, can improve environmental quality: at city scale mitigating urban heat island, improving outdoor comfort and providing additional benefits; at building scale, reducing the energy demand for cooling and favouring natural ventilation. In order to deeply address these aspects, the chapter comprises the analysis of case studies and monitoring activities related to urban greening, green roofs and vertical greening systems.

10.1 Urban Greening

Urban features and anthropic activities cause environmental degradation in cities and discomfort conditions. The amount of artificial surfaces with low albedo, car traffic, emissions due to industrial and domestic plants, the lack of green areas, building density, etc. are responsible for poor environmental quality and pollution. The urban heat island phenomenon, i.e. the temperature difference between cities and suburban or rural areas, is determined by the mentioned issues [1]. The phenomenon has been increasing in the past years [2, 3] also due to climate change, with relevant impacts of human health and increase in building energy consumption, especially

K. Perini (✉)
Dipartimento Architettura e Design, University of Genova, Genoa, Stradone S. Agostino 37, 16123 Genoa, Italy
e-mail: katia.perini@unige.it

G. Pérez
University of Lleida, Lleida GREiA Research Group, INSPIRES Research Centre, University of Lleida, Pere de Cabrera S/N, 25001 Lleida, Spain

G. Chiesa et al. (eds.), *Innovations in Ventilative Cooling*, PoliTO Springer Series,
https://doi.org/10.1007/978-3-030-72385-9_10

during summer [4]; for example, in Athens, cooling demand doubled due to ambient temperature increase [5]. In addition, air conditioning increases, itself, the Urban Heat Island phenomenon [6], causing an increase up to 2.56 °C in outdoor air temperature [7]. This is an important issue to consider in order to, from one side, reduce the buildings related energy consumption and emissions and, from the other, increase the thermal comfort of cities.

Urban greening can mitigate the urban heat island phenomenon and improve outdoor thermal comfort, as demonstrated by several authors [8–10], thanks to its cooling potential. In addition, vegetation in cities collects fine dusts, resulting in air quality improvement [11], contributes to sustainable water management [12, 13], provides acoustic insulation and noise reduction [14–16] and habitat for biodiversity [17, 18] with social and aesthetics effects [19–21].

In order to obtain the environmental benefits which urban greening can provide, a wide range of green infrastructure can be integrated in dense urban areas. These include: urban parks with different sizes, street trees, domestic gardens, green infrastructure specifically designed to improve water management, as rain gardens and vegetative swale. Vegetation at building scale can also be exploited for ventilative cooling, for the reduction of energy demand for air conditioning, for thermal comfort improvement; for such purpose green roofs and vertical greening systems can be an interesting option, as discussed in the Chapter.

10.2 Greening the Building Envelope

10.2.1 Green Roofs

A green roof is composed of layers that allow establishing and developing vegetation on the top of buildings. From top to bottom, above the structure of the roof, these layers are the vegetation layer, substrate layer, filter layer, drainage layer, protection and water retention layer, and finally the root barrier and waterproofing layer [22]. Although maintaining this basic multi-layer structure, three large groups of green roofs can be clearly differentiated; extensive, semi-intensive and intensive green roofs (Fig. 10.1).

Extensive green roofs are mainly designed to provide aesthetic and ecological benefits, being usually forbidden its pedestrian use. Main characteristics of extensive approach are its low cost, lightweight, minimal maintenance requirements (1–2 times per year) and the use of self-generative plant species. Intensive green roofs look like real "roof gardens" since they are designed and developed as public open spaces to be used as parks and/or building amenities. Thus intensive systems are characterized by higher weight and maintenance as well as intensive planting, ranging from lawns to shrubs and trees. Semi-intensive design try to avoid the extensive approach drawbacks under extreme climate conditions by increasing the thickness of some layers such as substrate and water retention layers, in order to

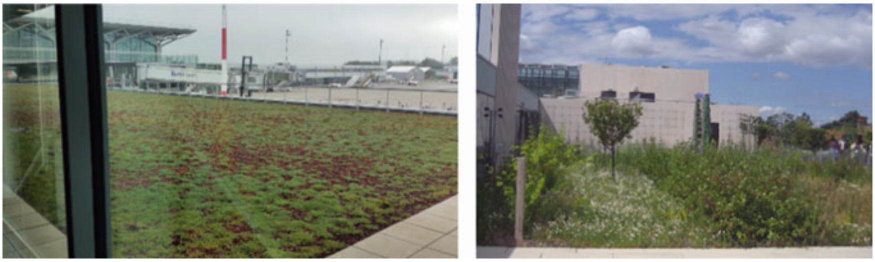

Fig. 10.1 Left: Extensive green roof. Zurich (Switzerland) 2017. Right: Intensive green roof. Greenwich (UK) 2015

Table 10.1 Main green roofs typologies and their characteristics

	Extensive	Semi-intensive	Intensive
Weight at field capacity	50–150 kg/m^2	120–350 kg/m^2	>350 kg/m^2
Substrate layer thickness	6-20 cm	10-25 cm	>25 cm
Plant species	Succulent, herbaceous and grasses	Herbaceous, grasses and shrubs	Grasses, shrubs and trees
Maintenance and irrigation	Low	Moderate	High
Use	Only accessible for maintenance (slope < 100%)	Pedestrian areas but with a moderate use (slope < 20%)	Pedestrian/recreation areas (slope < 5%)

guarantee the plants survival, but consequently the system weight and the required maintenance level are higher. Table 10.1 summarizes the main features of these three typologies of green roof [23, 24].

10.2.2 Vertical Greening Systems

Vertical greening systems are commonly classified as living wall systems and green façade, depending on the growing method and supporting structure used [25–27] (Fig. 10.2). Living wall systems are based on thin panels for the growth of different plant species, including shrubs and climbing plants. In order to provide water and nutrients to plants, an irrigation system is always included in the design of a living wall system and nutrients are periodically supplied. The many systems on the market use different materials for the supporting panels: felt or other textile layers overlapped on top of a waterproofing layer working as support (e.g. PVC panel) to create small pockets for the plants; plastic planter boxes filled with organic substrate, foam panels, etc. Living wall systems must be carefully designed, especially the irrigation system

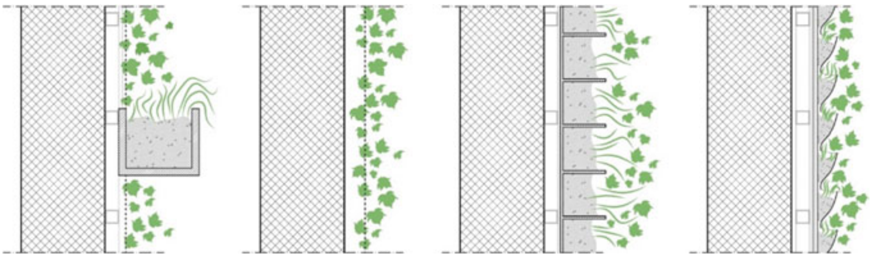

Fig. 10.2 Vertical greening systems: green façades (**a** with planter boxes and **b** indirect) and living wall systems (**c** plastic modular panel and **d** felt layers) [25]

to avoid the death of plants. These systems contribute to the building envelope performances, thanks to the materials involved [28], but entail often higher economic and environmental costs compared to green façades [29, 30].

Green façades are based on climbing plants rooting in front of a building (in the ground) or in planter boxes, placed also at different heights of a building (e.g. on terraces). Plants can be attached directly to the building envelope or to a supporting structure (indirect green façade), made of a steel mesh, wood or plastic structures. Maintenance is usually simple, costs lower as well as environmental impact [29, 30]. The use of supporting structure creates an air cavity, which has thermal benefits for the building envelope [31] and reduce the risk of damage to the façade.

10.3 Operating Methods

The benefits that greenery provides to the urban environment improvement and outdoor comfort, as well as to the passive energy savings in buildings and indoor comfort, are currently well known and reported [32]. The main mechanisms that regulate this set of ecosystem services provided by green roofs and VGS are basically four, the shade effect, the cooling effect, the insulation effect, and finally the wind barrier effect [33] (Table 10.2).

The *shade effect*, which is probably the most significant for the energy savings purpose, consists basically on the solar radiation interception provided by plants.

Table 10.2 Operating methods of urban vegetation for thermal and comfort benefits

Effect	Operating method
Shade	Solar radiation interception provided by plants
Cooling	Evapotranspiration from the plants and substrates
Insulation	Insulation capacity of the different construction system layers: plants, air, substrates, felts, drainage materials, etc.
Wind barrier	Wind effect modification by plants and substrates

The *cooling effect* takes place due to the water evapotranspiration process from the substrates (evaporation) and plants (transpiration). This effect has a double component since while heat energy is removed during the process, the relative humidity increases due to the evapotranspiration process, which implies a refreshment of the adjacent air layer. Ventilative cooling strategies could take advantage of this effect to increase its efficiency by means of the displacement of this fresh air towards areas where the aim is to reduce the temperature and raise relative humidity. In this regard, the water content on the substrate, and its capacity to store water, as well as the plant species used, are key aspects to consider.

The *Insulation effect* is related to the insulation capacity of the different materials used in the solution, especially the substrate and drainage layers, and their thickness.

Finally, the *wind barrier effect* refers to the capacity of green roofs to modify the direct wind effect on the building, either by cooling or by heating it.

Knowing these passive operating methods, it is necessary to look for ways to activate these systems and/or linking them to the ventilative systems in order to exploit all their cooling potential.

10.4 Greening Cities to Improve Environmental Conditions

Green areas in cities allow regulating air temperature, air flow, mean radiant temperature and relative humidity, with effects evident at a range of scales (city, district, canyon scale). In order to exploit the cooling capacity of vegetation, plant species characteristics are important (Table 10.3), as well as the position in relation to the built space. For example, trees planted in urban canyons, roadside or in the middle of a canyon, have different performances in terms of outdoor thermal comfort, since roadside greening reduces wind speed [34]. Plant species characteristics (in particular morphological properties) have different solar attenuation capacity [35]. Lee et al. [8] show that trees mitigate air temperatures up to 3.4 °C, while grassland up to 2.7 °C, mean radiant temperature reduction are respectively 39.1 and 7.5 °C and PET values 17.4 for trees and 4.9 for grassland.

Urban greening reduces high ambient temperatures in built environments, resulting in potential energy savings for cooling [39].

Green courtyards are traditionally used in some areas (e.g. the *patio* of the region of Andalucia, Spain) to favour natural ventilation: pressure difference between cooler and hotter areas increase natural ventilation (Fig. 10.3). When vegetation is planted in a courtyard, i.e. a small area within buildings, the humidity increases due to evapotranspiration, which implies a thermal energy absorption able to mitigate urban temperatures, with most of solar radiation transformed into latent heat [39]. Air flow direction and intensity can be regulated by means of trees and shrubs, and therefore exploited for natural ventilation. In addition, air passing through leaves is cooled by the mentioned mechanism.

Table 10.3 Main characteristics of vegetation affecting outdoor comfort parameters (based on [34, 36–38])

Foliage shape and dimensions
• Regarding mean radiant temperature, foliage determines shadow area, depending on the site latitude • Row/group of trees can create a barrier or increase air flow • Foliage affects plants evapotranspiration, which results in reduced air temperatures and increased air humidity
Height of trunk
• Regarding mean radiant temperature, trunk's height determines shadow area, depending on the site latitude • In order to protect from winter wind, trunks height should be reduced
Leaf area density (LAD)
• High values reduce the solar radiation transmitted during summer. • Leaf Area Density determines the air flow through the foliage (low or high) • LAD affects plants evapotranspiration, which results in reduced air temperatures and increased air humidity
Seasonal cycle
• Deciduous plant species avoid winter shading • Evergreen species are required for winter air flow control
Daily transpiration
• High levels of daily transpiration cool the air flow passing through trees • Transpiration implies a thermal energy absorption able to decrease summer overheating and increase air humidity

Fig. 10.3 Natural ventilation favoured by a green courtyard

Mean radiant temperature of buildings depends on material properties and therefore is influenced by the presence of green areas, trees, grassland, etc. *[40]. The shading effects of plants result in lower surface temperatures around 1–2* °C *at night and around 4-8* °C *during the daytime [39].*

By means of dynamic simulation, parametric design and genetic algorithms, the optimal position of trees around a 1-floor and a 2-floors building are identified for the city of Rome, to reduce the energy consumption for cooling. Results show that the shading effects of trees have a significant influence with an energy consumption decreases in a range of 11.1–12.8% for a 1-tree configuration, up to 48.5%. for a 5-trees configuration. The study shows also that east and west sides are most favourable positions to reduce energy consumption [41].

10.5 Greening Buildings and Ventilative Cooling to Improve Energy Performances and Thermal Comfort

The cooling capacities of vertical greening systems can be exploited to improve the energy performances of buildings and indoor thermal comfort. Several researches show that vertical greening systems and green roofs can be used as passive tool for energy savings at building scale [42]. The system characteristics highly influence the performances (e.g. green façades vs living wall systems, see par. 9.2.2), as well as plant species density (i.e. leaf area index, LAI), transpiration, etc. *[43], by means of Computational Fluid Dynamics (CFD) simulations, for which vegetation is modelled as porous medium, show that the design has to consider the coverage (block ratio) in order to obtain optimal ventilation performance.*

The shadow effect and evaporation capacities can be effectively exploited during cooling periods to improve indoor thermal comfort, resulting in energy savings for air conditioning and mechanical ventilation. The temperature difference created by a green layer can be exploited to increase natural ventilation (thanks to pressure differences). [44] study the improvements in indoor thermal comfort which can be obtained by adopting water-to-air heat exchangers (WAHE) and indirect evaporative and radiant cooling strategies in buildings with green roofs. According to the authors, future research should experimentally evaluate the system performance with a fan sensor that re-circulates the indoor air through the WAHE or provide natural ventilation as required according to seasonal variations. *In order to discuss these aspects, some case studies are presented.*

10.6 Case Studies and Monitoring Results

10.6.1 INPS Green Façade: A Pilot Project Built in Genoa, Italy

The pilot project and the monitoring activities

The INPS Green façade pilot project (Fig. 10.4) was installed on the south wall of INPS (National Institute of Social Insurance) headquarters in Sestri Ponente, Genoa (Italy) in 2014. The building envelope is exposed to solar radiation 8 h/day in summer and 1–2 h/day during winter and is made of two layers of masonry with a 51 cm air gap and a 5 cm of insulating layer (polystyrene), with a thermal transmittance of 0.44 W/m^{2}K. The geotextile panels of a living wall system cover 120 m^2; climbing plants placed in the panels grow on steel meshes (for additional 35 m^2 of the external

Fig. 10.4 The pilot project INPS Green Façade, Genoa (Italy)

wall). Several shrubs and climbing plants were planted in order to monitor their adaptation capacity and performances. Among these *Rhincosperma jasminoide, Hedera helix, Phlomis fruticose, Cistus Jessami beauty* can be mentioned. An irrigation system provides water and allows the plants survival.

Monitoring activities developed from 2014 to 2018 are focused on the environmental, economic and social benefits of the pilot project. Such monitoring activities include:

- a sociological investigation, implemented before and after construction [45, 46];
- sampling and analysis of leaves (plants: *Rhincosperma jasminoide, Hedera helix, Phlomis fruticose, Cistus Jessami beauty*) to compare the fine dusts collecting capacity [11];
- Field measurements of environmental parameters (air and surface temperature, relative humidity, solar radiation, etc.) to quantify the cooling performances of the system [47, 48];
- Cost benefit analysis to evaluate the economic sustainability of INPS green façade pilot project [49];
- Life cycle assessment to evaluate the environmental sustainability of INPS green façade pilot project (preliminary results in [50]).

A thermographic analysis was performed before and after the installation of the vertical greening system in order to, first of all, highlight the structure of the building and the presence of thermal bridges and, after the installation, the surface temperature difference (Figs. 10.5 and 10.6).

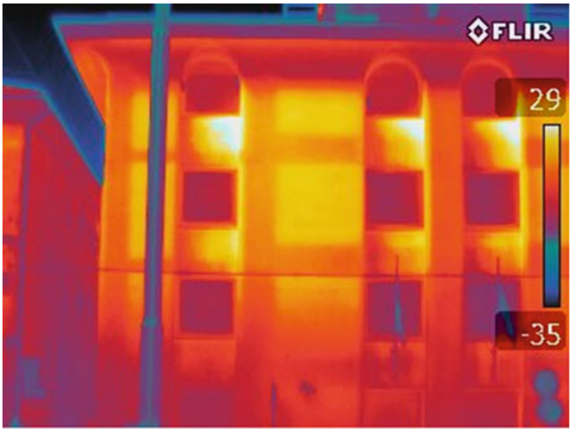

Fig. 10.5 Photo of the facade made with infrared camera before the installation

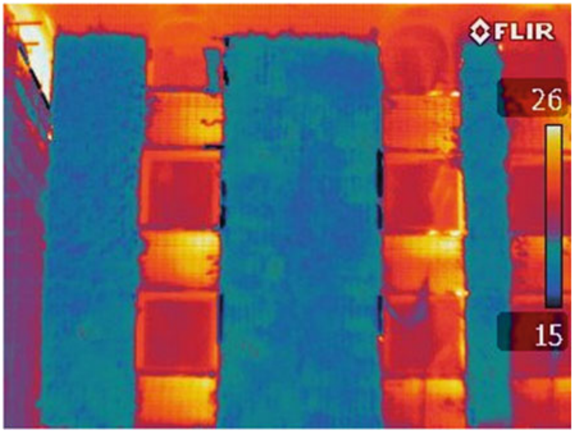

Fig. 10.6 Photo of the INPS Green façade with infrared camera before the installation

Thermal performances

As described previously in the chapter, vertical greening system have interesting performances in terms of cooling potential, which could be exploited for indoor ventilation and air conditioning. The summer monitoring campaign performed on INPS Green Façade focused on such aspects [47, 49]. The main quantities analysed are (Fig. 10.7): external surface temperatures in presence and in absence of the vertical greening system; solar radiation, outdoor air temperature and humidity are also monitored. In order to monitor a potential air temperature difference to be exploited for indoor ventilation and air conditioning, two 8 cm diameter ducts were made throughout the building wall, of which one is below the green layer, provided with a resistance temperature detector. Air is extracted by means of an impeller (Axial fan a.c. 80 x 80 x 25mm, max air flow 41 m^3*h^{-1}) from the gap between the vertical greening system and the external wall and from outside, allowing a continuous comparison between the data recorded.

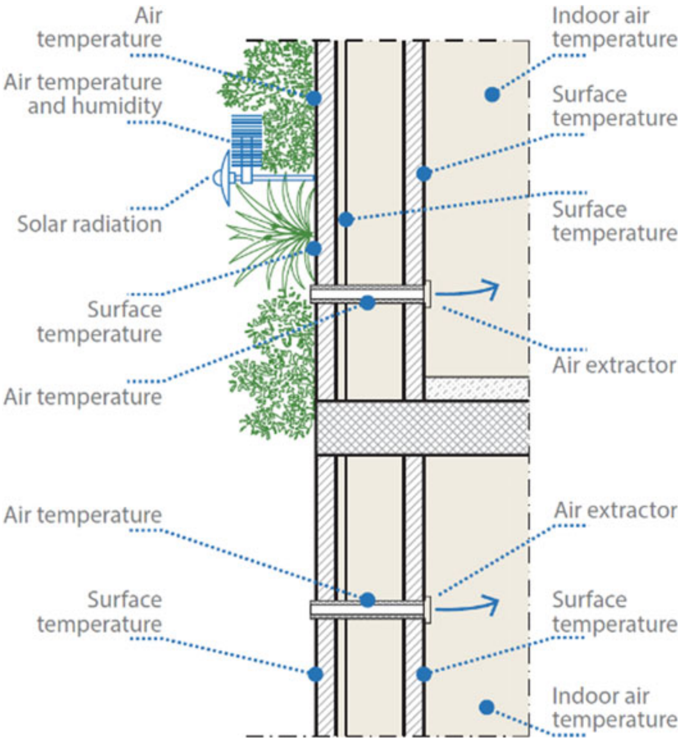

Fig. 10.7 Energy monitoring system [49]

The results of the monitoring campaign, performed during summer 2015-2016-2017 from the 1st June to the 30th September (for 2017 the month of September is not considered), are presented in Table 10.4. The data analysed are related to a public office building occupancy hours i.e. from 8 A.M. to 6 P.M. Data show monthly average air temperature difference between green and no green in a range of 1.5 up to 6 °C. In addition, the monthly number of office hours during which the air with and without the influence of the greening system exceeds 26 °C[1] are measured. Results show that, thanks to the cooling potential of the green layer, the number of hours with Tair > 26 °C is 0 in most of the month, with exception for July and August 2015 (respectively 19 and 6).

The cooling potential of the VGS can be used for makeup air, by means of devices placed in each room (an example in Fig. 10.8). During summer, cooler fresh makeup air can reduce the room thermal energy need for air conditioning, thanks to the decrease of room thermal load. The use of extracted air behind vertical greening systems for natural ventilation (makeup air) represents an interesting option to exploit the cooling capacity of vegetation. In addition, a pressure difference between the

[1]The indoor temperature used for calculating the energy need for space cooling in *Italian standard UNI/TS 11300-1*.

Table 10.4 Monthly average temperatures, calculated during office hours (from 8 AM to 6 PM), of air extracted from the two ducts, with and without influence of the VGS and monthly number of office hours (from 8 A.M. to 6 P.M.) during which the air exceeds 26 *°C*

Month	Air extracted from outside [°C]	Number of hours that air, extracted from outside, temperature exceeds 26 °C	Air extracted behind vertical greening system [°C]	Number of hours that air, extracted from outside, temperature exceeds 26 °C
June 2015	26.5	119	21.3	0
July 2015	29.8	208	24.6	19
August 2015	27.3	143	22.7	6
September 2015	23.0	44	19.2	0
June 2016	25.6	77	22.6	0
July 2016	23.8	161	21.7	0
August 2016	21.3	112	18.3	0
Septembe 2016	23.2	7	21.1	0
June 2017	22.2	138	20.7	0
July 2017	25.6	125	23.7	0
August 2017	26.3	117	20.1	0

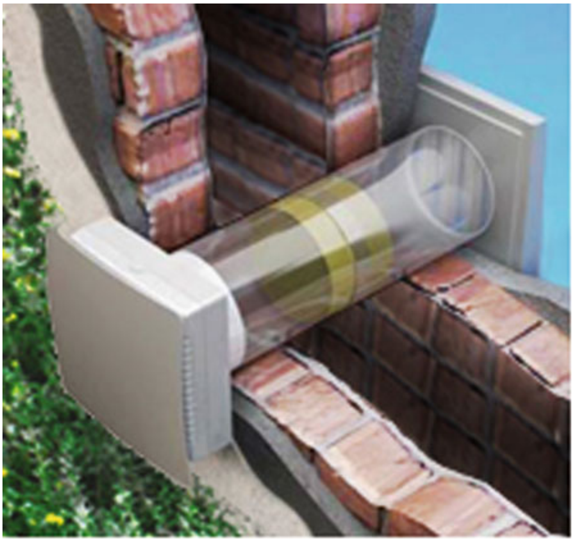

Fig. 10.8 Example of a fresh air inlet device

side of a building with a greening system and the roof and or another façade could be exploited. For mechanical ventilation additional research is needed in order to evaluate the cooling capacity of a vertical greening system with higher air flows.

The presented results show that vertical greening system could play a relevant role for indoor thermal comfort improvement and energy savings, providing cooler air for mechanical and natural ventilation.

10.6.2 Experimental Research Results in Lleida, Catalonia (Spain)

During the last decade, set of experimental investigations focused on the study of green roofs and vertical greening systems have been conducted at the University of Lleida (Catalonia, Spain). Main objective of these experiments was the study of these nature-based solutions contribution to passive energy savings in buildings while sustainable criteria were applied to the new designed solutions.

In all of them, the great potential of these systems to improve the thermal performance of the building envelope was observed, which entails great savings in energy consumption as result of the combined effect of the shadow, evapotranspiration, insulation and wind barrier, mainly provided by plants and substrates.

Unlike the grey infrastructure, urban green infrastructure also contributes via cooling effect to the improvement of the environment, whether internal or external, thanks to the modification of the temperature and relative humidity in its surroundings. Latent heat of water vaporization accounts for 2.45 MJ Kg^{-1} (20 °C), and this takes place both from plants and from substrates during the process of evapotranspiration. By means of the combination of this process and ventilation, either natural or artificial, it is possible to shift these improvements though the building spaces.

Green roofs

Experimental set-up on the thermal performance of extensive green roofs.

In this study it was intended to measure the potential of extensive green roofs as a passive energy saving system in buildings under Mediterranean continental climate. Two identical extensive green roofs of 9 cm thick (4 cm for drainage layer and 5 cm for substrate layer) were implemented in two identical 3 × 3 × 3 m experimental cubicles. The main aim was to characterize their contribution as passive energy saving systems in buildings [51–53]. The only difference between these green roofs was the drainage material used, that was pozzolana in one cubicle and recycled rubber crumbs in the other. These two cubicles, in which no additional insulation layer was installed on the green roof profile, were compared with a third reference cubicle with a conventional flat roof insulated with 3 cm of sprayed polyurethane, finished with gravel ballast (Fig. 10.9). The plants used were a mixture of *Sedum sp.* and *Delosperma sp.*

From the results of this experimentation it was concluded that a 9 cm extensive green roof without additional insulation offered better thermal insulation than a conventional isolated flat roof in cooling periods, but lower in heating periods. The

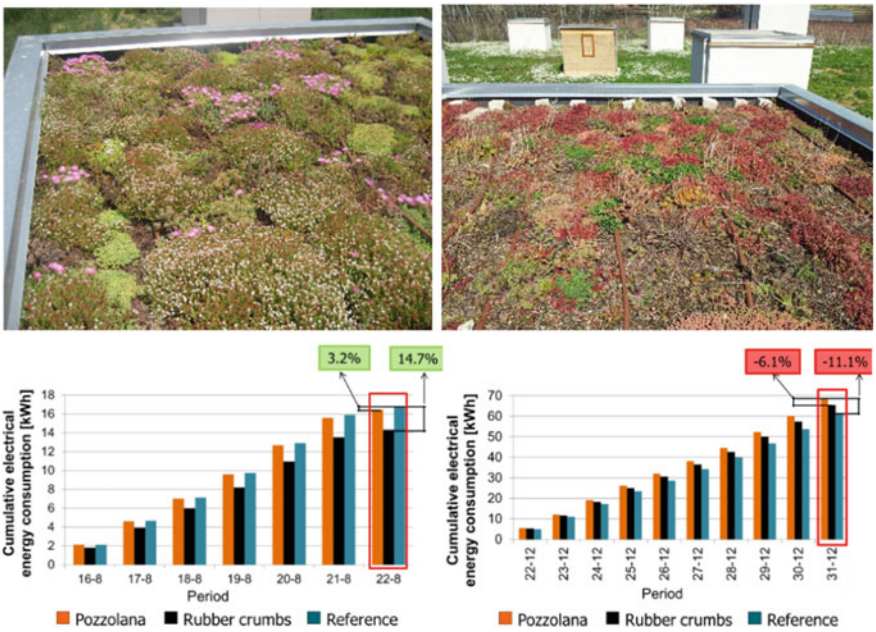

Fig. 10.9 Experimental extensive green roofs in the "Puigverd de Lleida" pilot plant of GREiA research group—University of Lleida. Pictures and results for the energy consumption during summer (left) and winter (right) periods [51–53]

measured reductions on the roof surface temperatures were a clear indicator of the influence of shade and cooling effects on the energy consumption reduction.

10.6.3 A Case Study. 4-Year Monitoring of Green Roofs at Lleida Agri-Food Science and Technology Park (Catalonia, Spain)

With the aim of characterizing the thermal behavior and the evolution of the plants (*Sedum sp.),* an extensive 2000 m^2 green roof located in the Lleida Agri-food Science and Technology Park (Catalonia, Spain) was monitored during four years after its implementation [54, 55] (Fig. 10.10).

From this experiment, very interesting conclusions were drawn regarding the substrate behavior and the fact that 100% plant coverage was hardly achieved under this Continental Mediterranean climate. These facts had a double connotation. On the one hand, the bare substrate becomes extremely hot on surface, reaching more than 50 degrees during the summer season. On the other hand, the lack of rain water available for long periods can reduce the cooling effect at times that are most needed,

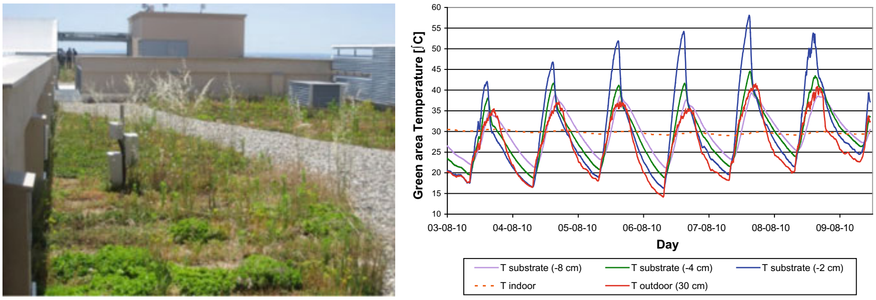

Fig. 10.10 Green roof "aljibe" typology on the Lleida Agri-food Science and Technology Park (Catalonia, Spain). Results for temperatures through the roof profile [54, 55]

that is summer periods. For this reason, it is very important to design systems thinking not only on the plant survival but also about the ecosystem services provided by green infrastructure, in this case the evaporative cooling effect.

In this regard, the establishment of an irrigation regime in extensive green roofs during the summer periods for these extreme climates would allow improving the vegetal coverage and, at the same time, increasing the evapotranspiration capacity and consequently the cooling effect of the system.

Vertical greening systems

Experimental set-up on the thermal performance of vertical greening systems (VGS).

In a complete experimentation, two different vertical greening systems were installed in two identical experimental cubicles of 3 x 3 x 3 m with the objective of evaluating their potential as passive systems of energy saving in buildings [53, 56, 57] (Fig. 10.11). In the first cubicle, a green facade was implemented in the East, South and West orientations, by means of a steel mesh separated 20 cm from the building facade and Boston ivy (*Parthenocissus tricuspidata*). On the second cubicle, a green wall, constituted by modules of recycled plastic and aromatic shrubs (*Rosmarinus* and *Helicrissum*) was also placed on the same three orientations. A third identical cubicle in which no one greening system was placed was used as reference for the experimentation.

In this experiment, positive results were obtained so that the ability to save energy during summer periods was really very high. The relationship between the vertical solar irradiation and the reduction of the energy consumption provided by the two vertical systems was also found (Fig. 10.11).

In winter, unlike what is usually said in the non-specialized bibliography, very promising results were observed. Thus, relating to green facade, the cubicle on which this system was placed, behaved equal to the reference cubicle as it was expected, due to the deciduous condition of Boston ivy. On the other hand, the green wall cubicle recorded a slight reduction of 4%, which means a slightly insulating capacity but with a large margin for improvement in the design of these construction system.

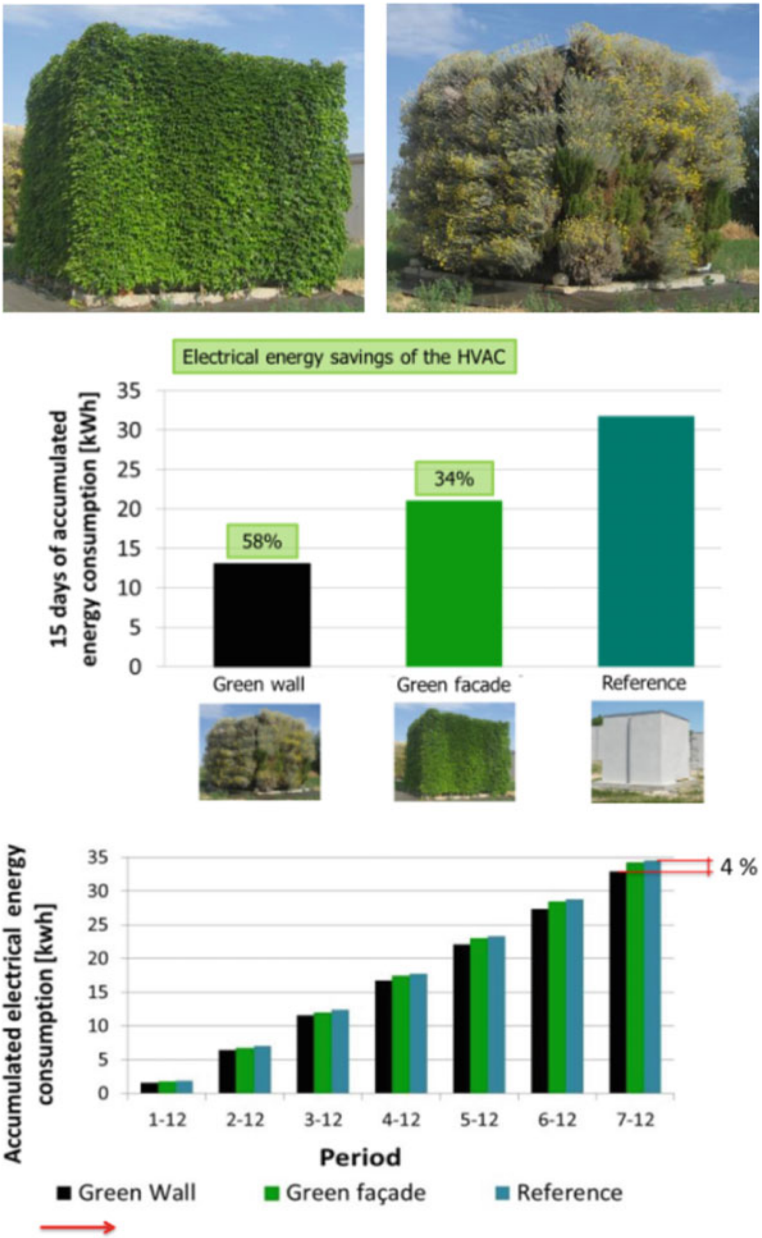

Fig. 10.11 Left: Green facade on the experimental cubicle and results of summer energy consumption. Right: Green wall on experimental cubicle and winter results [53, 56, 57]

Although in these experimentation the passive use of VGS for energy savings was the main aim, the good performance of green systems by reducing the surface temperatures of façade building, due to the shadow effect, and the contribution of evapotranspirative cooling from plants and substrates, suggest an interesting potential to combine them to the mechanical ventilation systems.

10.6.4 Case Study. 2-Year Monitoring of a Double-Skin Green Façade at the Theatre of Golmés Green Facade (Golmés, Catalonia, Spain)

In this study, a glycine double-skin green façade (*Wisteria sinensis*) located in the village of Golmés, Lleida was monitored during two years. From this case study, interesting conclusions regarding the potential of green facades as passive systems of energy saving in buildings were obtained [58, 59] (Fig. 10.12).

Fig. 10.12 Golmés double-skin green facade (Golmés, Catalonia, Spain)

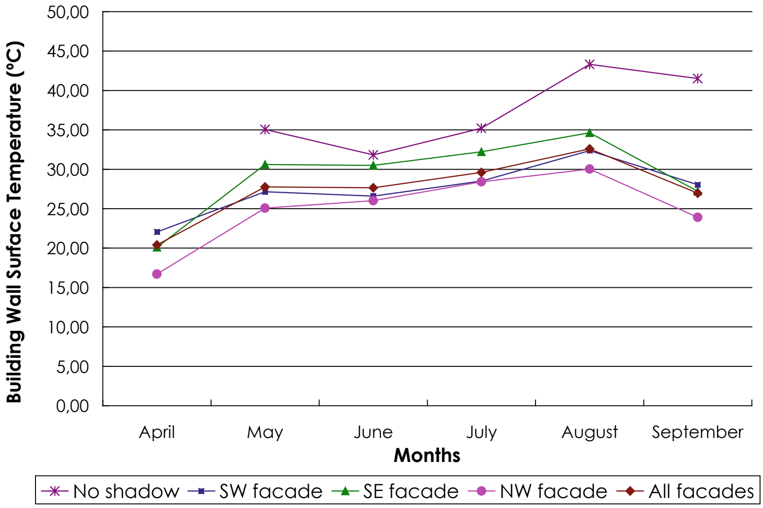

Fig. 10.13 Building wall surface temperature measured at the Golmés green façade, in 2009

The good thermal performance was due to, not only the shadow effect, that is the direct interception of the solar radiation, but specially as a consequence of the microclimate generated in the intermediate space between the green screen and the building facade wall. In this sense, the contribution of the cooling effect by means of transpiration from plants was very significant.

As a consequence of greenery the building wall surface temperature in sunny areas was on average 5.5 °C higher than in shaded areas. This difference was higher in August and September, reaching maximum values of 17.6 °C on the North West side in September (Fig. 10.13).

Of particular interest were the measured temperatures and relative humidity in the intermediate space between the green screen and the building façade wall. Slightly lower temperatures and higher relative humidity in the intermediate space than outside were measured in the hottest months (May, June, July, and August), when the foliage reached the maximum foliage density (Fig. 10.14).

Again, in these experiments only the passive contribution of the VGS was measured. However, the good results obtained, especially those referring to the improvement of humidity and temperature conditions in the intermediate space between the green screens and the building facade, imply a great potential to be combined with ventilative cooling systems to consequently improve the thermal performance of the whole building.

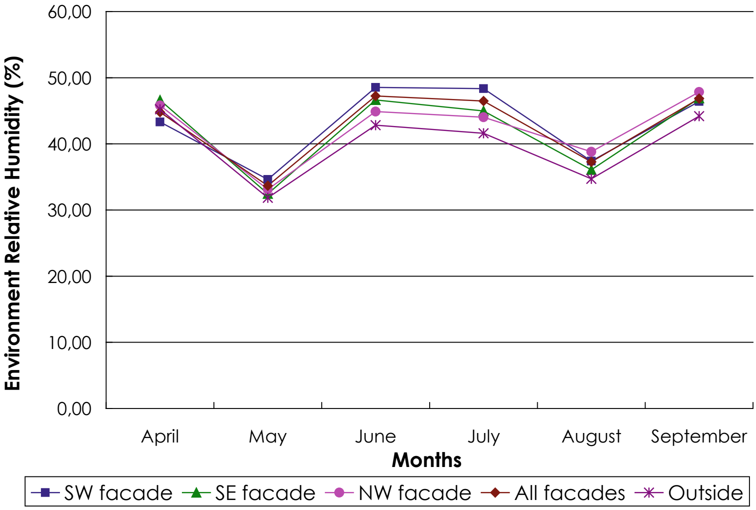

Fig. 10.14 Environment relative humidity measured at the Golmés green façade, in 2009

10.7 Suggestions for Future Research

At view of the great potential in terms of passive cooling effect of greening systems for the building envelope, in particular of vertical greening systems, research should be oriented at the activation of these systems. Such activation can be obtained by recirculating the fresh air generated in the spaces near the green layer toward indoor spaces of the building. In order to implement such systems, the current construction systems should be re-designed with the aim of maximizing the cooling potential, for example by considering the creation of intermediate spaces between vegetation and buildings to store fresh air.

Other possibilities would be to select plant species for greening systems with a greater water transpiration capacity, as well as to establish different irrigation regimes to maximize evapotranspiration. Finally, future research should be oriented to the integration of cool air produced by greening system into building ventilation facilities.

In general, urban greening, even if not connected with the ventilate system of a building, can play an important role in cooling the microclimate, compensating the effect of electrical appliances and machinery, as well as indoor-outdoor heat exchanges that produce artificial air conditioning systems.

Acknowledgements The research presented from the University of Lleida (UdL) has been developed by the GREiA research group at UdL. These investigations have been partially funded by the Government of Spain (Projects: ENE2008-06687-C02-01/CON, ENE2011-28269-C03-02, ENE2011-28269-C03-03, ENE2015-64117-C5-1-R, ENE2015-64117-C5-3-R, ULLE10-4E-1305), the European Union (COST Action COST TU0802, Seventh Framework Program - FP/2007–2013 under Grant agreement No. PIRSES-GA-2013-610692 - INNOSTORAGE, Horizon 2020 research and innovation program under grant agreement No. 657466 - INPATH-TES), the Government of Catalonia for the quality accreditation granted to the GREiA group during these years (2009 SGR 534, 2014 SGR 123) and to the Fundación Mapfre. The authors especially want to thank the collaboration with the companies Soprema, Gestión Medioambiental de Neumáticos S.L, y Buresinnova S.A, as well as the City Councils of Golmés and Puigverd de Lleida. Julià Coma would like to thank the Ministerio de Economia y Competitividad de España for the Juan de la Cierva Grant, FJCI-2016-30345.

The research presented regarding INPS Green Façade has been financed by the Research Fund for the Italian Electrical System under the Contract Agreement between RSE S.p.A. and the Ministry of Economic Development – General Directorate for Nuclear Energy, Renewable Energy and Energy Efficiency stipulated on July 29, 2009 in compliance with the Decree of March 19, 2009. This research is part of the monitoring activity carried out to quantify environmental and energy performances of vertical greening systems funded by INPS (National Institute of Social Insurance) Liguria.U. Valle (INPS Liguria) is thanked for his important support.

References

1. Taha H (1997) Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. Energy Build 25:99–103. https://doi.org/10.1016/S0378-7788(96)00999-1
2. Hasanean HM (2001) Fluctuations of surface air temperature in the Eastern Mediterranean 68, pp 75–87. https://doi.org/10.1007/s007040170055
3. Rozbicki T, Golaszewski D (2003) Analysis of local climate changes in Ursynów in the period 1960–1991 as a result of housing estate development. In: Proc. 5th Int. Conf. Urban Climate, pp 455–458
4. Akbari H (2005) Energy saving potentials and air quality benefits of urban heat IslandMitigation
5. Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, Argiriou A, Assimakopoulos DN (2001) On the impact of urban climate on the energy consumption of buildings. Sol Energy 70:201–216. https://doi.org/10.1016/S0038-092X(00)00095-5
6. Nakamatsu R, Tsutsumi JG, Arakawa R (2003) Relations of energy consumption and local climate in a subtropical region
7. Wen Y, Lian Z (2009) Influence of air conditioners utilization on urban thermal environment. Appl Therm Eng 29:670–675. https://doi.org/10.1016/j.applthermaleng.2008.03.039
8. Lee H, Mayer H, Chen L (2016) Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany. Landsc Urban Plan 148:37–50. https://doi.org/10.1016/j.landurbplan.2015.12.004
9. Perini K, Magliocco A (2014) Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort. Urban For Urban Green. https://doi.org/10.1016/j.ufug.2014.03.003
10. Petralli M, Prokopp A, Morabito M, Bartolini G, Torrigiani T, Orlandini S (2006) Ruolo delle aree verdi nella mitigazione dell'isola di calore urbana: uno studio nella città di Firenze. Rivista Italiana di Agrometeorologia 1:51–58
11. Perini K, Ottelé M, Giulini S, Magliocco A, Roccotiello E (2017) Quantification of fine dust deposition on different plant species in a vertical greening system. Ecol Eng 100:268–276. https://doi.org/10.1016/j.ecoleng.2016.12.032
12. Fioretti R, Palla A, Lanza LG, Principi P (2010) Green roof energy and water related performance in the Mediterranean climate. Build Environ 45:1890–1904. https://doi.org/10.1016/j.buildenv.2010.03.001
13. Sabbion P (2018a) Chapter 3.12 - green streets to improve water management. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 215–225. https://doi.org/10.1016/B978-0-12-812150-4.00020-3

14. Lacasta AM, Peñaranda A, Cantalapiedra IR (2018) Chapter 3.9 - Green streets for noise reduction. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 181–190. https://doi.org/10.1016/B978-0-12-812150-4.00017-3
15. Pérez G, Coma J, Cabeza LF (2018a) Chapter 3.7 - Vertical greening systems for acoustic insulation and noise reduction. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 157–165. https://doi.org/10.1016/B978-0-12-812150-4.00015-X
16. Van Renterghem T (2018) Chapter 3.8 - green roofs for acoustic insulation and noise reduction. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 167–179. https://doi.org/10.1016/B978-0-12-812150-4.00016-1
17. Atkins E (2018) Chapter 3.15 - green streets as habitat for biodiversity. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 251–260. https://doi.org/10.1016/B978-0-12-812150-4.00023-9
18. Collins R, Schaafsma M, Hudson MD (2017) The value of green walls to urban biodiversity. Land Use Policy 64:114–123. https://doi.org/10.1016/j.landusepol.2017.02.025
19. Kotzen B (2018) Chapter 4.2 - green roofs social and aesthetic aspects. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 273–281. https://doi.org/10.1016/B978-0-12-812150-4.00025-2
20. Magliocco A (2018) Chapter 4.1 - vertical greening systems: social and aesthetic aspects. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 263–271. https://doi.org/10.1016/B978-0-12-812150-4.00024-0
21. Sabbion P (2018b) Chapter 4.3 - green streets social and aesthetic aspects. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 283–290. https://doi.org/10.1016/B978-0-12-812150-4.00026-4
22. Breuning J, Yanders AC (2008) FLL guidelines for the planning, construction and maintenance of green roofing
23. Nyuk Hien W, Puay Yok T, Yu C (2007) Study of thermal performance of extensive rooftop greenery systems in the tropical climate. Build Environ 42:25–54. https://doi.org/10.1016/j.buildenv.2005.07.030
24. Pérez G, Coma J (2018) Chapter 2.3 - green roofs classifications, plant species, substrates. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 65–74. https://doi.org/10.1016/B978-0-12-812150-4.00006-9
25. Fernández-Cañero R, Pérez Urrestarazu L, Perini K (2018) Chapter 2.1 - vertical greening systems: classifications, plant species, substrates. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 45–54. https://doi.org/10.1016/B978-0-12-812150-4.00004-5
26. Köhler M (2008) Green facades—a view back and some visions. Urban Ecosyst 11:423–436. https://doi.org/10.1007/s11252-008-0063-x
27. Perini K, Ottelé M, Haas EM, Raiteri R (2012) Vertical greening systems, a process tree for green façades and living walls. Urban Ecosyst 16:265–277. https://doi.org/10.1007/s11252-012-0262-3
28. Coma J, Pérez G, de Gracia A, Burés S, Urrestarazu M, Cabeza LF (2017) Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green facades. Build Environ 111:228–237. https://doi.org/10.1016/j.buildenv.2016.11.014
29. Ottelé M, Perini K, Fraaij ALA, Haas EM, Raiteri R (2011) Comparative life cycle analysis for green façades and living wall systems. Energy Build 43:3419–3429. https://doi.org/10.1016/j.enbuild.2011.09.010

30. Perini K, Rosasco P (2013) Cost–benefit analysis for green façades and living wall systems. Build Environ 70:110–121. https://doi.org/10.1016/j.buildenv.2013.08.012
31. Hunter AM, Williams NSG, Rayner JP, Aye L, Hes D, Livesley SJ (2014) Quantifying the thermal performance of green façades: a critical review. Ecol Eng 63:102–113. https://doi.org/10.1016/j.ecoleng.2013.12.021
32. Besir AB, Cuce E (2018) Green roofs and facades: a comprehensive review. Renew Sustain Energy Rev 82:915–939. https://doi.org/10.1016/j.rser.2017.09.106
33. Pérez G, Perini K (eds) (2018) Nature based strategies for urban and building sustainability. Butterworth-Heinemann, Oxford, United Kingdom
34. Perini K, Chokhachian A, Auer T (2018) Chapter 3.3 - green streets to enhance outdoor comfort. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann (Elsevier), Oxford, United Kingdom, pp 119–129. https://doi.org/10.1016/B978-0-12-812150-4.00011-2
35. Morakinyo TE, Kong L, Lau KK-L, Yuan C, Ng E, n.d. A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort. Building and environment. https://doi.org/10.1016/j.buildenv.2017.01.005
36. Grosso M (2012) La Ventilazione Naturale Controllata e il Raffrescamento Passivo Ventilativo degli edifici [WWW Document]. http://porto.polito.it/2579961/. Accessed 2 Feb 17)
37. Perini K (2013) Progettare il verde in città: una strategia per l'architettura sostenibile. F. Angeli, Milano
38. Scudo G, Ochoa de la Torre JM (2003) Spazi verdi urbani: la vegetazione come strumento di progetto per il comfort ambientale negli spazi abitati. Sistemi editoriali : Esselibri-Simone, [Napoli]
39. Wong NH, Chen Y (2009) The role of urban greenery in high-density cities. In: Designing high-density cities: for social and environmental sustainability. Routledge, pp 87–106
40. Chokhachian A, Perini K, Dong S, Auer T (2017) How material performance of building façade affect urban microclimate, in: powerskin conference| proceedings. In: Delft TU (ed) Presented at the powerskin conference. Delft, The, Netherlands, pp 83–96
41. Calcerano F, Martinelli L (2016) Numerical optimisation through dynamic simulation of the position of trees around a stand-alone building to reduce cooling energy consumption. Energy Build 112:234–243. https://doi.org/10.1016/j.enbuild.2015.12.023
42. Pérez G, Coma J, Cabeza LF (2018b) Chapter 3.1 - Vertical greening systems to enhance the thermal performance of buildings and outdoor comfort. In: Pérez G, Perini K (eds) Nature based strategies for urban and building sustainability. Butterworth-Heinemann, Oxford, United Kingdom, pp 99–108. https://doi.org/10.1016/B978-0-12-812150-4.00009-4
43. Yuan C, Shan R, Adelia AS, Tablada A, Lau SK, Lau SS-Y (2019) Effects of vertical farming on natural ventilation of residential buildings. Energy Build 185:316–325. https://doi.org/10.1016/j.enbuild.2018.12.028
44. Berardi U, La Roche P, Almodovar JM (2017) Water-to-air-heat exchanger and indirect evaporative cooling in buildings with green roofs. Energy Build 151:406–417. https://doi.org/10.1016/j.enbuild.2017.06.065
45. Magliocco A, Perini K, Prampolini R (2015) Qualità ambientale e percezione dei sistemi di verde verticale: un caso studio. In: Abitare Insieme - Living Together. Presented at the Abitare il Futuro - 3° edizione, Clean Edizione, Università di Napoli Federico II - Dipartimento di Architettura. Napoli, Italy, pp 1462–1417
46. Magliocco A, Perini K (2015) The perception of green integrated into architecture: installation of a green facade in Genoa, Italy. AIMS Environ Sci 2(4):899–909. https://doi.org/10.3934/environsci.2015.4.899
47. Perini K, Bazzocchi F, Croci L, Magliocco A, Cattaneo E (2016a) The use of vertical greening systems to reduce the energy demand for air conditioning. Field monitoring in mediterranean climate. In press
48. Perini K, Magliocco A, Giulini S (2016b) Vertical greening systems evaporation measurements: does plant species influence cooling performances? Int J Vent 0:1–9. https://doi.org/10.1080/14733315.2016.1214388

49. Rosasco P, Perini K (2018) Evaluating the economic sustainability of a vertical greening system: a Cost-Benefit Analysis of a pilot project in mediterranean area. Build Environ 142:524–533. https://doi.org/10.1016/j.buildenv.2018.06.017
50. Magrassi F, Perini K (2017) Environmental and energetic assessment of a vertical greening system installed in Genoa, Italy. Presented at the International Conference on Urban Comfort and Environmental Quality (URBAN-CEQ), Genova University Press, Genova, pp 132–136
51. Coma J, Pérez G, Solé C, Castell A, Cabeza LF (2016) Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. Renew Energy 85:1106–1115. https://doi.org/10.1016/j.renene.2015.07.074
52. Pérez G, Vila A, Rincón L, Solé C, Cabeza LF (2012) Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material. Applied energy, energy solutions for a sustainable world - Proceedings of the Third International Conference on Applied Energy, May 16–18, 2011 - Perugia, Italy 97:347–354. https://doi.org/10.1016/j.apenergy.2011.11.051
53. Coma J, Pérez G, Solé C, Castell A, Cabeza LF (2014) New green facades as passive systems for energy savings on buildings. Energy Procedia, 2013 ISES Solar World Congress 57, pp 1851–1859. https://doi.org/10.1016/j.egypro.2014.10.049
54. Bevilacqua P, Coma J, Pérez G, Chocarro C, Juárez A, Solé C, De Simone M, Cabeza LF (2015) Plant cover and floristic composition effect on thermal behaviour of extensive green roofs. Build Environ 92:305–316. https://doi.org/10.1016/j.buildenv.2015.04.026
55. Perez G, Vila A, Solé C, Coma J, Castell A, Cabeza LF (2015) The thermal behaviour of extensive green roofs under low plant coverage conditions. Energy efficiency in press. https://doi.org/10.1007/s12053-015-9329-3
56. Pérez G, Coma J, Sol S, Cabeza LF (2017) Green facade for energy savings in buildings: the influence of leaf area index and facade orientation on the shadow effect. Appl Energy 187:424–437. https://doi.org/10.1016/j.apenergy.2016.11.055
57. Pérez G, Coma J, Martorell I, Cabeza LF (2014) Vertical Greenery Systems (VGS) for energy saving in buildings: a review. Renew Sustain Energy Rev 39:139–165. https://doi.org/10.1016/j.rser.2014.07.055
58. Pérez Gabriel, Rincón L, Vila A, González JM, Cabeza LF (2011) Green vertical systems for buildings as passive systems for energy savings. Appl Energy 88:4854–4859. https://doi.org/10.1016/j.apenergy.2011.06.032
59. Pérez G, Rincón L, Vila A, González JM, Cabeza LF (2011) Behaviour of green facades in Mediterranean continental climate. Energy Convers Manag 52:1861–1867. https://doi.org/10.1016/j.enconman.2010.11.008