Universitat de Lleida

# Green roofs and vertical greenery systems as passive tools for energy efficiency in buildings

Julià Coma Arpón

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# TESI DOCTORAL

# Green roofs and vertical greenery systems as passive tools for energy efficiency in buildings

Julià Coma Arpon

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
Programa de Doctorat en Informàtica i Enginyeria Industrial

Director/a
Prof. Dr. Luisa F. Cabeza
Dr. Gabriel Pérez

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**Directors de la Tesis:** Dra. Luisa F. Cabeza i Dr. Gabriel Pérez

La Dra. Luisa F. Cabeza, Catedràtica de l’Escola Politècnica Superior de la Universitat de Lleida i el Dr. Gabriel Pérez, professor agregat de l’Escola Politècnica Superior de la Universitat de Lleida.

CERTIFIQUEN:

Que la memòria “Green roofs and vertical greenery systems as passive tools for energy efficiency in buildings” presentada per Julià Coma Arpon per optar al grau de Doctor s’ha realitzat sota la seva supervisió.

Lleida, 4 d’Agost de 2016

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# Resum

El consum total d’energia al sector de l’edificació ha estat incrementant des de l’any 1971, arribant en l’actualitat a representar el 33% del consum final de l’energia global. El sector serveis, representa una quarta part del total, mentre que les tres quartes parts restants d’aquesta energia es consumida pel sector residencial, essent la calefacció i refrigeració els responsables del 40% del consum d’energia als edificis.

D’acord amb l’informe de *Energy Technology Prespectives 2016*, la demanda d’energia i les emissions de carboni haurien de reduir-se al menys en un 30% al 2050, havent-se d’emprendre accions immediates als edificis. En aquesta línia, estudis realitzats per l’Agència Internacional de l’Energia, afirmen que realitzar millores en la envolvent dels edificis pot contribuir a reduir la demanda energètica fins a un 40% al 2050.

En aquest context, durant l’última dècada les infraestructures verdes urbanes (sostres verds i sistemes verds verticals) implementades en la pell dels edificis han esdevingut prometedors sistemes d’estalvi energètic passiu i de reducció de les emissions de $CO_2$ en els entorns urbans. A més a més, aquests sistemes ofereixen molts beneficis (*ecosystem services*) tant a nivell ecològic, econòmic com social en un mateix entorn mitjançant solucions naturals.

El principal objectiu d’aquesta tesi és analitzar dos d’aquests *ecosystem services* quan s’implementen infraestructures verdes als edificis. D’una banda, s’analitza l’eficiència energètica del sostres verds extensius i sistemes verds verticals per tal d’avaluar el seu potencial com a sistemes passius d’estalvi d’energia, mentre que per altra banda, s’avalua experimentalment la capacitat d’aïllament acústic de dos sistemes verds verticals (façanes i murs verds).

A més a més de proporcionar dades quantitatives d’aquests *ecosystem services* per cobrir una manca de resultats experimentals en la literatura, aquesta tesis també té com a objectiu analitzar l’impacte mediambiental dels sostres verds extensius per tal d’estudiar la seva sostenibilitat.

# Resumen

El consumo total de energía en el sector de la edificación ha estado incrementando des del 1971, llegando hoy en día a representar el 33% del consumo de la energía global. El sector servicios, representa una cuarta parte del total, mientras que las tres cuartas partes restantes de esta energía son consumidas por el sector residencial, siendo calefacción y refrigeración las responsables del 40% del consumo de energía en los edificios.

De acuerdo con el informe de *Energy Technology Prespectives 2016*, la demanda de energía y las emisiones de carbono deberían reducir-se al menos en un 30% en el 2050, debiéndose emprender acciones inmediatas en los edificios. En esta línea, estudios realizados por la Agencia Internacional de la Energía afirman que realizar mejoras en las envolventes de los edificios puede contribuir a reducir la demanda de energía hasta un 40% en el 2050.

En este contexto, durante la última década las infraestructuras verdes urbanas (techos verdes y sistemas verdes verticales) implementadas en la envolvente de los edificios se han convertido en prometedores sistemas pasivos de ahorro energético y de reducción de las emisiones de $CO_2$ en los entornos urbanos. Además, estos sistemas ofrecen muchos beneficios (*ecosystem services*) tanto a nivel ecológico, económico como social en un mismo entorno mediante soluciones naturales.

El principal objetivo de esta tesis es analizar dos de estos *ecosystem services* cuando se implementan infraestructuras verdes en los edificios. De un lado, se analiza la eficiencia energética de los techos verdes extensivos y sistemas verdes verticales para evaluar su potencial cómo sistemas de ahorro de energía pasivos, mientras que del otro lado, se evalúa experimentalmente la capacidad de aislamiento acústico de dos sistemas verdes verticales (fachadas y muros verdes).

Además de proporcionar datos cuantitativos de estos *ecosystem services* para cubrir una falta de resultados experimentales en la literatura, esta tesis también tiene el objetivo de analizar el impacto medioambiental de los techos verdes extensivos para estudiar su sostenibilidad.

# Summary

The total energy consumption of the building sector has been growing since 1971 arriving nowadays at 33% of the global final energy consumption. The services sub-sector, accounts for one-quarter of this consumption, whereas the remaining three-quarter parts of this energy is consumed by the residential sub-sector, being the space heating and cooling the 40% of the global buildings energy use.

According to the Energy Technology Perspectives 2016, the primary energy demand and carbon emissions should be reduced over 30% by 2050, and hence immediate priorities in buildings need to be implemented. In this frame, studies delivered by the International Energy Agency stated that improvements in building envelopes can contribute to more than 40% of the energy savings expected by 2050.

Within this context, the use of urban green infrastructures (green roofs and vertical greenery systems) on building envelopes have become more popular during the last decade as promising passive solutions regarding the energy consumption and $CO_2$ emissions in built environments. Moreover, they offer multifunctional benefits (ecosystem services) at ecological, economic, and social levels at the same spatial area through natural solutions.

The main objective of this PhD thesis is to analyse two of these ecosystem services when green infrastructures are applied on buildings. On one hand, the energy efficiency of extensive green roofs and vertical greenery systems is studied to evaluate their potential as a passive energy saving systems, and on the other hand, the sound insulation capacity provided by two different vertical greenery systems (green facades and green walls or living walls) is experimentally tested.

Besides providing quantitative data for some ecosystem services to address the lack of experimental results in the literature, this thesis is also focused on analysing the environmental impact of extensive green roofs in order to study their sustainability.

## Nomenclature

| | |
|---|---|
| **ESS** | Ecosystem services |
| **GI** | Green infrastructures |
| **GR** | Green roofs |
| **GW** | Green walls or living walls |
| **GF** | Double-skin green facade |
| **HVAC** | Heating ventilation and air conditioning |
| **VGS** | Vertical greenery systems |

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# 1 Introduction

## 1.1 Energy use in the building sector

Being the building sector (residential and services) responsible of about 33 % of the global final energy consumption and the one-third of total direct and indirect $CO_2$ emissions, the significant reduction in both figures are key targets for all countries for the next decades [1]. According to the Energy Technology Perspectives (ETP) 2016 of the International Energy Agency, the primary energy demand and carbon emissions should be reduced over 30% and 70%, respectively, by 2050 [2].

The total energy consumption of the building sector has been growing 1.8% per year since 1971, reaching 117 EJ in 2010. The services sub-sector, accounted 25% of this consumption, whereas the remaining three-quarter parts of this energy (82 EJ) was consumed by the residential sub-sector as shown in Figure 1. Globally, the energy demand in buildings is dominated by space heating and cooling, especially in cities, which represents almost 40% of the global buildings energy use [2].

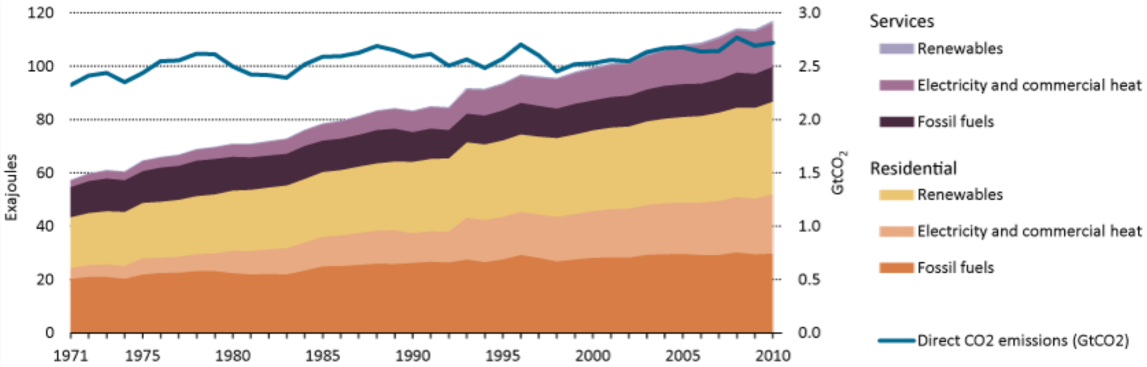

Figure 1. Global buildings energy consumption by energy source and direct CO2 emissions [1]

In addition to the present detailed scenarios and energy saving strategies for 2050 for buildings, the study delivered by the International Energy Agency (IEA) “Transition to Sustainable Buildings” emphasizes the necessity of implementing immediate priorities in buildings, such as high performance building envelopes, high efficiency equipment, and new strategies to address the energy consumption in this sector [1]. These priorities need to be applied in both new and refurbished buildings, since half of the current global building stock is expected to be standing in 2050.

The thermal performance of building envelope components, including roof, walls, basement, windows, and ventilation/air leakage, is critical to determine the energy requirements for heating and cooling [3]. Besides, they also provide security, fire and weather protection, structural integrity, aesthetics, etc.

More than 40% of the savings expected by 2050 in Europe (EU) can be directly attributed to improvements in building envelopes, as shown in Figure 2 [1]. Therefore, their improvement is the first target and one of the most potential ways to reduce the overall energy demand in this sector.

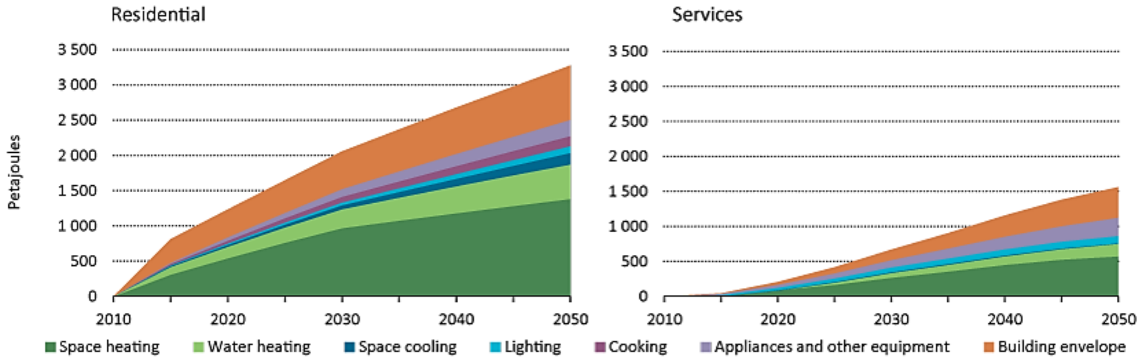

Figure 2. Energy savings perspectives to 2050 in EU in the residential and services sub-sectors [1]

Within this context, the use of green infrastructures (GI) at urban scale and especially in buildings have become more popular during the last decade, contributing in many of the benefits well described in the abovementioned strategies, with promising contributions on reducing the energy demand and $CO_2$ emissions in the built environment [4].

## 1.2 Green infrastructure to promote urban ecosystem services

Nowadays there are many definitions to describe what green infrastructures are, and what the main benefits are provided to the society (ecosystem services). However, regarding the typology of green infrastructures and the field of their implementation (urban, peri-urban and rural), they can widely contribute in different ecosystem services. Therefore, to continue within the scope of this PhD, only definitions about green infrastructures and their valuable benefits in the urban environment when applied as building envelopes were explored.

Recently, besides providing a comprehensive study of GI in buildings and urban environments, John Dover [5] proposed a new definition based on an extensive literature review, where:

*"Green infrastructure is the sum of an area's environmental assets, including stand-alone elements and strategically planned and delivered networks of high-quality green spaces and other environmental features including surfaces such as pavements, car parks, driveways, roads and buildings (exterior and interior) that incorporate biodiversity and promote ecosystem services."*

In order to better understand the GI concept, Figure 3 shows some examples of GI when are applied in an urban environment.

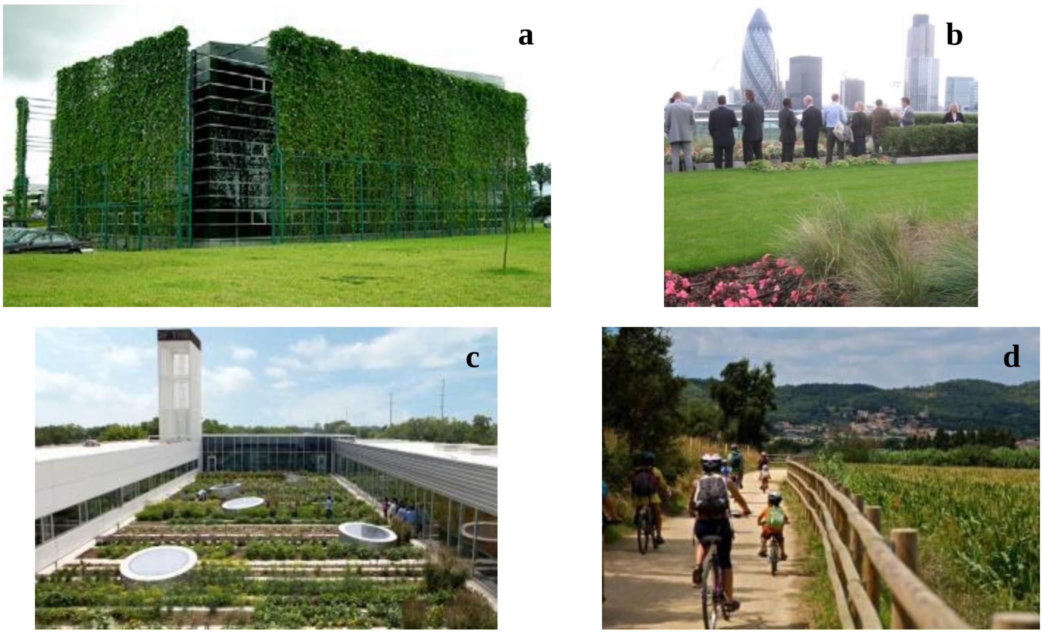

Figure 3. Examples of GI in urban areas; (a) Green facade, TRIBU building, Costa Rica; (b) Intensive green roof, London; (c) Extensive green roof, Rooftop Haven for Urban Agriculture, Chicago; (d) Green road in Riudaura, Olot

With more than 54% of the world population living in urban areas, a percentage that is expected to increase up to 66% by 2050, especially in EU which is currently 66% [6], GI have become successful tools to provide multifunctional benefits at ecological, economic, and social levels at the same spatial area through natural solutions [7]. The GI development in urban areas is one way to help offset the losses caused by ecosystems fragmentation over the years due to the urbanisation, industrialisation, and the continued expansion of grey infrastructure [8]. These systems also could deal with the objectives of the European framework programme Horizon 2020, which are mainly focused on promoting the energy efficiency in buildings, industry, heating and cooling, SMEs and energy-related products and services, integration of ICT and cooperation with the telecom sector [9].

Within this context, many projects of GI in Denmark, France, Germany, Austria, Netherlands, and Spain among others, which promote GI in urban and peri-urban areas, are found [10]. However, end-use policies for their implementation at building scale are still scarce or do not exist. Thus, new end-use policies at European, national, regional and local levels should be delivered, to promote the research and the implementation of these technologies in buildings.

In spite of helping to maintain a healthy environment and to contribute significantly to achieve many of the EU key policy objectives, GI can deliver valuable services (or benefits) to society and wildlife, also known as ecosystem services (ESS) [11].

In the first large scale ecosystem assessment, with the aim to link the ecosystem services and human well-being, four primary categories were proposed in the Millennium Ecosystem Assessment (MA) [12]:

- Provisioning services – products obtained from ecosystems.
- Regulating services – benefits obtained from the regulation of ESS.
- Supporting services – the necessary services for the production of all other ESS.
- Cultural services – the non-material benefits obtained from ESS.

Onwards, with the same objective and to better understand the economic value of ESS and the tools that take into account this value, The Economics of Ecosystems and Biodiversity (TEEB) [13] proposed an extended classification where 24 ecosystem services are sorted based on the same categories than MA, as shown in Table 1.

Table 1. Classification of the 24 different ecosystem services sorted by ME categories

| Provisioning services | Regulating services | Habitat/supporting services | Cultural services |
|---|---|---|---|
| • Food<br>• Raw materials<br>• Fresh water<br>• Medical resources<br>• Genetic resources<br>• Ornamental resources | • Local Climate regulation<br>• Air quality regulation<br>• Carbon sequestration/storage<br>• Moderation of extreme events<br>• Waste-water treatment<br>• Regulation of water flows<br>• Erosion prevention<br>• Maintenance of soil fertility<br>• Pollination<br>• Biological control<br>• Maintenance of life cycles of migratory species | • Habitats for species<br>• Maintenance of genetic diversity | • Recreation and mental and physical health<br>• Tourism<br>• Aesthetic appreciation and inspiration for culture, art and design<br>• Spiritual experience and sense of place<br>• Information for cognitive development |

The concept of ESS is well framed at global scale as well as it provides a useful tool for policymakers and other stakeholders, to evaluate the potential benefits of GI for the society. However, GI are relatively a new concept and the lack of quantitative analysis and the complexity to identify adequate indicators to assess its multifunctional benefits (ecological, economic and social), hinders the possibility to create adequate policies and initiatives to promote its final implementation [7]. Figure 4 shows the main ESS related to buildings and urban environment, their attributes and also some examples of their direct and indirect values for the human being.

To provide a better comprehension of the ESS values, the following definitions have been summarized [13]:

- Direct use values: those most likely to be priced in markets, that can be counted and/or are directly related to obtain profits from the ecosystem (e.g. food, row materials, fresh water, energy savings, etc.).
- Indirect use values: those are recently emerged to be assigned an economic value (e.g. water purification, carbon sequestration, local climate regulation, pollination, etc.).
- Non-consumptive use values or non-use values: Those that may include the spiritual or cultural importance of a landscape or species, but these benefits are rarely valued in monetary terms (e.g. recreation, aesthetics, spiritual or cultural landscape relevance, etc.).

| Aspect | Attributes | Examples |
|---|---|---|
| Visual | Aesthetics, screening | Improved visual environment |
| Human Health | Exercise (walking, running, green gym), pollution, abatement, de-stressing, socialisation, recreation | Reduced costs to health providers through reduced admissions; improved mental health; faster recovery |
| Education | Study and experience of wildlife, schools, ranger services, volunteering | Formal and informal education, skills through volunteering, hobbies (photography, bird watching, etc.) |
| Food Production | Allotments, gardens, orchards, roofs, walls | Improved diet, community bonding, education, biodiversity, exercise |
| Transport | Alternative movement corridor for cyclists and pedestrians | Reduces road congestion, safer routes, reduced pollution exposure, more relaxed setting |
| Economics | Property prices, inward investment, tourism, improved business / shopping environment | Improved staff morale, reduced sick-leave, improved staff retention, attracts businesses; units let faster and fewer voids |
| Climate Control | Reduced heat-related mortality, heat island, and wind; improved air circulation and climate change mitigation | Provides shade against UV-related cancer, cardiovascular mortality, heatstroke, etc.; reduces air and surface temperature, freshens air |
| Sustainable Urban Drainage | Reduced runoff, flash flooding | Reduces risk, economic losses, trauma and distress, processing costs |
| Pollution Control | Water, light, noise, air pollution (particulates, gases and aerosols, odours) | Removes $PM_{10}$ and below from air; absorbs nitrogen oxides, ozone, volatile organic chemicals; acts as heavy metal sink |
| Energy Efficiency | Reduces air conditioning and heating costs | Insulates buildings, provides shelter against drafts, shades windows |
| Biodiversity | Wildlife habitat, wildlife corridors and stepping stones | Provides breeding habitat, food and other resources; promotes dispersal; reduces extinction risks |

Figure 4. The main ecosystem services provided by green infrastructure when is applied in buildings and urban environments [5]

Within this context, when GI are applied on building envelopes (green roofs and vertical greenery systems), they are not only useful tools to address the global energy consumption and $CO_2$ emissions issues but also they can deliver many of the abovementioned ecosystem services [4,5], such as energy efficiency in buildings, pollution control, enhance the biodiversity, human health, improving the visual environment, and the quality of life in cities as better places to live [14].

## 1.3 Use of green infrastructure on building envelopes

The implementation of GI systems on buildings are becoming popular as passive tools to reduce their energy demand [15], to reduce the $CO_2$ concentration in large cities [16], to restore the fragmented ecosystem in grey areas, and thus provide many benefits for the society aside from their good aesthetics [17].

There are currently two main ways to implement GI on buildings envelopes that are green roofs (GR) and vertical greenery systems (VGS).

### 1.3.1 Green roofs (GR)

According to the literature [18-20], GR are classified in two main groups, intensive and extensive systems. Furthermore, the International Green Roof Association (IGRA) [21] suggested an intermediate category called semi-intensive GR. In Table 2, all the different GR types are classified according to final use, construction factors and the maintenance required during their operational lives.

Table 2. Classification of green roofs according to final use, construction factors and maintenance requirements [15]

| |  |  |  |
|---|---|---|---|
| | Extensive Green Roof | Semi-Intensive Green Roof | Intensive Green Roof |
| Maintenance | Low | Periodically | High |
| Irrigation | No | Periodically | Regularly |
| Plant communities | Moss-Sedum-Herbs and Grasses | Grass-Herbs and Shrubs | Lawn or Perennials, Shrubs and Trees |
| System build-up height | 60 - 200 mm | 120 - 250 mm | 150 - 400 mm on underground garages > 1000 mm |
| Weight | 60 - 150 kg/m$^2$ | 120 - 200 kg/m$^2$ | 180 - 500 kg/m$^2$ |
| Costs | Low | Middle | High |
| Use | Ecological protection layer | Designed Green Roof | Park like garden |

Among these systems, the extensive ones are the most implemented around the world, because they require less maintenance compared to intensive and semi-intensive and do not represent an excessive overweight for conventional roof structures, so that the reinforcement of the building structure is not required. Furthermore, according to several authors [22,23], after implement 100-150 mm of substrate thickness, the variability of the thermal performance is very low.

Their contribution as systems that provide interesting environmental benefits is well known since more than two decades ago. GR have high potential to reduce the energy consumption in buildings [24-25], to improve the storm water retention [26], to reduce the heat island effect [27-28] among other several advantages. However, some issues referring to these contributions must be addressed. Thus, studies regarding the thermal performance in winter time under different climate condition, the substrate composition, the environmental assessment of the materials used in different layers, and the thermal performance depending on the development of the vegetation, are still scarce in the literature and should be studied in depth. In addition, to go a step forward in this topic, more long term experimental data are necessary.

### 1.3.2 Vertical greenery systems (VGS)

In comparison with GR, there is no established standardization for VGS designs and its variations, making difficult the comparisons between them. However, Pérez et al. [29] provided a classification of VGS where both traditional and newly developed systems are considered as show in Table 3. According to the cost of implementation and further maintenance during the operational life, the author classified these systems into two main categories, extensive and intensive. Also, the classification differentiates the typology of VGS in two categories living walls or green walls and green facades.

After perform a cost-benefit analysis for different VGS, Perini et al. [30] stated that initial investment and maintenance of VGS have an important role on the economic sustainability. In addition, this study agree with the statements done by Pérez et al. [29], where extensive systems are easy to build and requires minimum maintenance, whereas intensive systems have a complex implementation and require high levels of maintenance and extra cost during the implementation.

Table 3. Classification of VGS for buildings [29].

| | Extensive systems | | Intensive systems |
|---|---|---|---|
| Green facades | Traditional green facades | --- | --- |
| | Double-skin green facade or green curtain | Modular trellis | --- |
| | | Wired mesh | --- |
| | | --- | Perimeter flowerpots |
| Living walls | --- | --- | Panels |
| | --- | --- | Geotextile felt |

The main differentiation is between green facades (GF) and green walls (GW) or living walls. On one hand, GF are systems in which climbing vegetation is developed using a structural support in order to cover the desired areas of the building facades. Thus, the vegetation can be planted directly on the ground level or in pots at different heights of the facade. As shown in Figure 5, GF are mainly divided in traditional green facades (where the vegetation is directly in contact with building walls) and double-screen green facades (where the vegetation is separated from building walls using modular trellises, wired, and mesh structures).

Figure 5. Left, traditional green facade in Lleida (Spain); right, double-skin green facade in Pergola building (Costa Rica), architect Bruno Santiago

On the other hand, GW are made of panels and/or geotextile felts, which contain the growing medium (substrate) for the plants, as shown in Figure 6. These systems require a sub-structure anchored to the walls to withstand the loads of the overall system (irrigation system, pots/modular panels/geotextiles, substrate, water and vegetation).

Figure 6. Green walls or living walls. Left, GW made of geotextile felt in Caixa Forum building, Madrid; right, GW made of panels in Multimedia Kyoto building (Japan), by Suntory Midory

Traditionally, these systems have been used primarily for aesthetics purposes [31], whereas nowadays they have become interesting systems to be implemented in buildings as potential passive solutions to enhance the quality of life in dense urban areas [15].

The main environmental benefits of these systems when they are applied on building envelops are similar to those of GR. Likewise, VGS can protect the building envelope from overheating through shading effect [32], they can reduce the wind speed on the walls [33], as well as, they provide energy savings in summer periods.

However, more studies concerning the thermal performance of the different typologies of VGS must be performed, especially in winter periods for different climate conditions. Furthermore, experimental data for both, GW and GF are scarce in the literature, and a lack of energy savings studies provided by these passive systems are still missing. Studies regarding the leaf area index (LAI) of the species used, the noise reduction, the foliage thickness, are also topics that need to be addressed in deep.

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# 2 Objectives

The main objective of this PhD thesis is to analyse the performance of two different green infrastructure systems (extensive green roofs and vertical greenery systems) and to study their potential as a passive energy saving system in buildings to reduce the heating and cooling demand in a Mediterranean continental climate conditions. Besides providing quantitative data for some ecosystem services, an environmental impact analysis of extensive green roofs and experimental analysis of the sound insulation capacity of VGS are also objectives of this PhD. To accomplish the aim of this thesis several specific objectives, divided in the following two main topics, are defined:

Green roofs:

- To study experimentally the thermal performance of two different new extensive green roofs without insulation layer and to determine their potential in reducing the cooling demand during summer period when the vegetation was in a growth phase.
- To evaluate the thermal performance of the two aforementioned extensive green roofs when the vegetation was completely developed, to determine their potential in reducing both, cooling and heating demands during the whole year.
- To evaluate the environmental impact of four different roof systems, two extensive green roofs (pozzolana and rubber crumbs without insulation) and two conventional (with and without insulation) through their whole life cycle.

Vertical greenery systems (VGS):

- To review the VGS used as passive tools for energy efficiency in buildings.
- To analyse experimentally the Leaf Area Index (LAI) for a double-skin green facade and to study its influence on the building thermal performance in summer.
- To study experimentally two different VGS (green wall and new double-skin green facade) in summer and winter conditions and to evaluate their potential in reducing the cooling and heating demands.
- To evaluate experimentally the acoustic insulation capacity of VGS when are used on building walls.

# 3 PhD thesis structure

The PhD thesis is based on seven papers; five of them have been already published in SCI journals while the other two have been submitted.

This thesis is framed in the long-term investigation on green infrastructure (GI) in buildings that GREA research group started some years ago with the aim to increase the energy efficiency in buildings, while improves at the same time, the sustainability of the built environment.

The structure of the PhD thesis is divided into green roofs (GR) and vertical greenery systems (VGS), which are the most common ways to implement GI in buildings.

In order to continue with the GREA planning, the first step was building three houses-like cubicles in order to study the benefits of two different extensive green roofs (with pozzolana and rubber crumbs as drainage layer) in terms of energy consumption and to compare them with a common insulated flat roof in a Mediterranean continental climate.

First of all, to analyse the importance of the substrate and drainage layers in extensive green roofs, the thermal performance during the summer 2011 after the plantation of the vegetation, when only 20 % of extensive green roofs were covered by the vegetation was studied and presented in Paper 1.

The next step (Paper 2) consisted of assessing the thermal performance of the same cubicles with the vegetation completely developed and considering a whole year 2012 analysis, in which the summer and winter periods were included.

After that, the results obtained during the summer and winter experiments related to energy consumption during the operational phase were used to perform an LCA analysis of these systems. In Paper 3, an environmental comparison between four different roof construction systems, two extensive green roofs (rubber crumbs and pozzolana), and two common flat roofs (with and without insulation layer) was carried out.

On the other hand, to start the research on VGS topic, a comprehensive literature review about their implementation as passive energy saving systems in buildings was presented in Paper 4. This study showed the lack of literature in relation to some ecosystem services such as energy efficiency and noise insulation capacity provided by VGS.

After that, the next step consisted of to characterize the leaf area index (LAI) in a double-skin green facade (GF), which is the main factor related to evaluate the shade effect and consequently to evaluate the potential as a passive system. For this purpose, a methodology to be applied on VGS was proposed. Furthermore, a relation between LAI and energy savings was found and presented in Paper 5.

Moreover, so as to evaluate the potential of an intensive GW and extensive GF as passive systems in buildings, the thermal performance during summer and winter, with and without controlled indoor temperatures was analysed and presented in Paper 6. Also, an evaluation of the thermal performance of walls depending on the facade orientation was presented for both green systems.

Finally, to provide quantitative data and to address the lack of knowledge of these two VGS as acoustic insulation tools for buildings, experimental tests were performed and presented in Paper 7.

All the papers presented in the thesis are organized as shown in Figure 7.

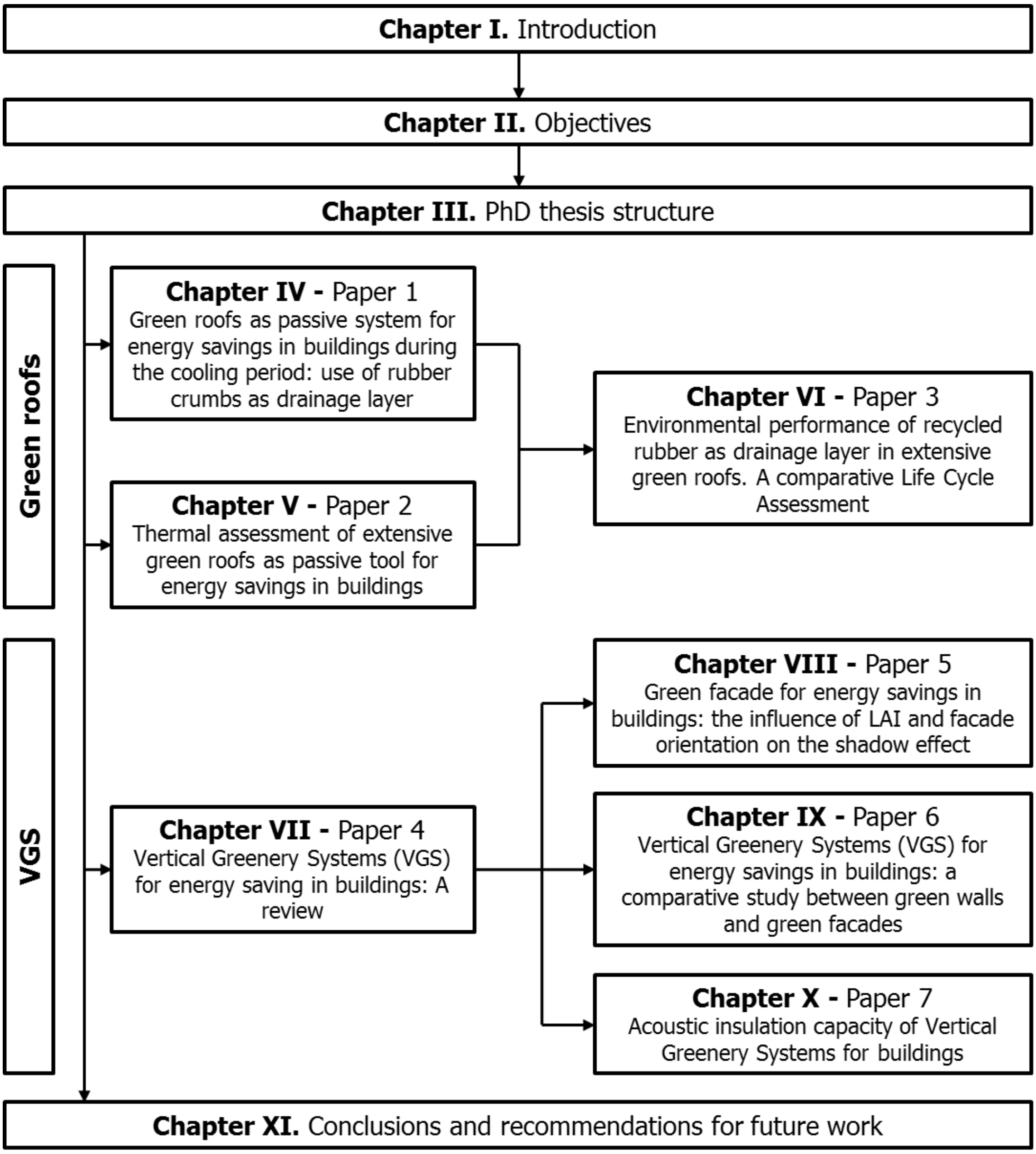

Figure 7. PhD structure scheme

# 4 Green roofs as passive system for energy savings in buildings during the cooling period: use of rubber crumbs as drainage layer

## 4.1 Introduction

The European Union (EU) directives concerning to the reduction of energy demand in buildings [1] are still a priority in the framework of the objectives Horizon 2020. Nevertheless, the process to apply these regulations is a long term plan that provides time to the scientific community to develop new or enhanced construction systems, materials, buildings facilities, etc.

Referring to the energy efficiency in buildings, green roofs are suitable to contribute in reducing passively the energy consumption during the lifetime of the building as shown in literature [2,3]. In addition, these systems provide other several benefits for buildings such as: storm water retention capacity [4], capturing the $CO_2$ emissions [5], increasing the durability of internal membranes [6], increasing the biodiversity in cities [7]. However, several gaps about the effectiveness of extensive green roofs as passive energy saving systems in different climate conditions, especially during low vegetation cover periods e.g. after plantation, have been found.

## 4.2 Contribution to the state-of-the-art

In order to better understand the thermal performance and energy consumption of extensive green roofs in Mediterranean areas, one of the overall objectives of this paper is to provide a real scale comparison for three identical house-like cubicles, where the only difference between them is the construction roofing system. Two of cubicles have 9 cm depth extensive green roofs without insulation (comparing rubber crumbs and pozzolana as drainage materials) while the reference cubicle had a conventional flat roof with insulation. The experimental results and details about this research are presented in:

- J. Coma, G. Pérez, A. Castell, C. Solé, L.F. Cabeza. Green roofs as passive system for energy savings in buildings during the cooling period: use of rubber crumbs as drainage layer. Energy Efficiency 2014;7:841-849.

This paper provides a step forward in terms of comparing the energy efficiency of two different extensive green roofs systems in Mediterranean Continental climate conditions during the first summer after planting the vegetation. In addition, to show the potential implementation of these green systems, without insulation, a comparison with a common insulated flat roof used in standard buildings has been performed.

In order to compare the thermal performance of the inner environment and the energy consumption of the HVAC systems of three different house-like cubicles, two types of tests have been carried out. The first one consists of maintaining the inner environment in a comfort range during the cooling period using an HVAC system. Accordingly to the ASHRAE standards [8], the comfort range for cooling purposes is between 23 ºC and 26 ºC. Therefore a set point of 24 ºC was used to evaluate the thermal behaviour. The second test consists of comparing the thermal performance of inner environment under free floating conditions, when no HVAC system is used.

The main results obtained in this paper shows that, even the green roof area covered by plants was only 20 % of the total surface, both extensive green roof provided energy savings during cooling periods (5 % for rubber crumbs and 14 % for pozzolana) in comparison to the reference roof system (Figure 8).

On the other hand, the results of experiments without HVAC systems also showed similar trends where the cooling performance of green roofs systems was higher. Both showed 1.5 ºC lower internal ceiling temperature profiles compared to the reference roof (Figure 9).

The results highlight that internal layers (substrate and drainage) of extensive green roofs play an important role in the overall thermal performance of these systems especially when the area covered by the vegetation is scarce.

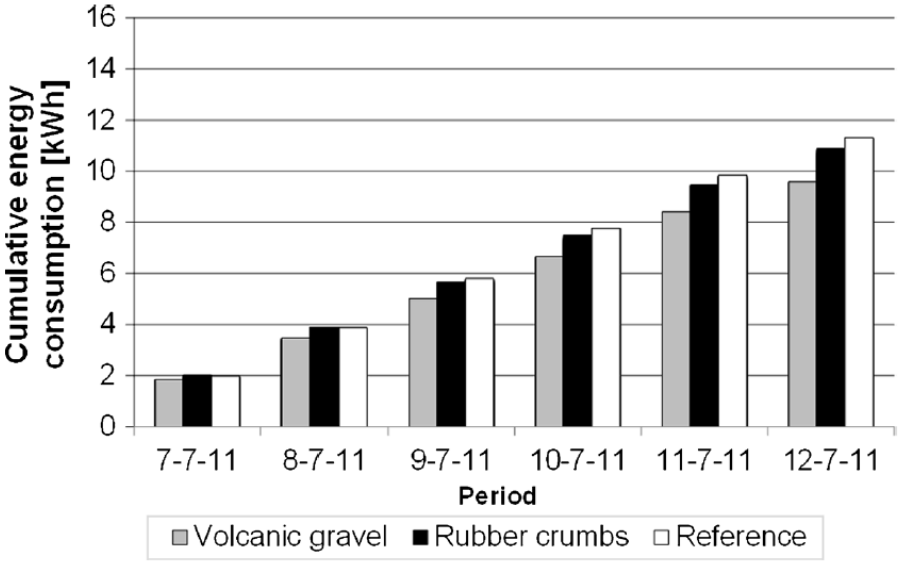

Figure 8. Cumulative electrical energy consumption. Controlled temperature (set point 24 ºC), first week of July 2011

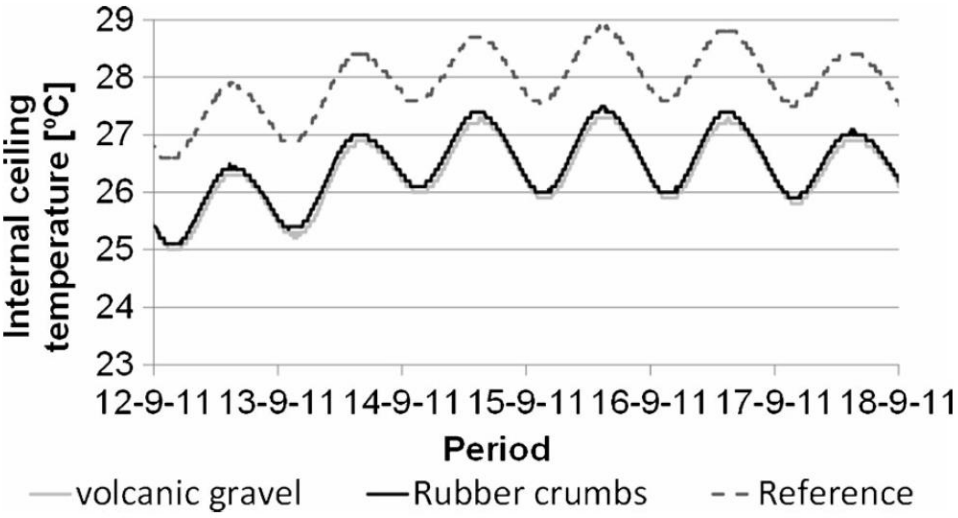

Figure 9. Internal ceiling temperatures of different cubicles under free floating conditions, third week of September 2011

On the other hand, from this study it can be verified how a simple 9 cm extensive green roof without insulation layer provides better cooling performance in comparison to an insulated flat roof typically used in buildings under Mediterranean Continental climate.

In addition, this system also provides a representative reduction of the internal ceiling surface temperature when the HVAC system is not used.

## 4.3 Contribution of the candidate

The research group started in green infrastructure (GI) topic few years before the candidate began the PhD, being green roofs (GR) the one of the main topics of experimental research as a passive energy saving system. Then, the tests presented in this paper were performed by the candidate in order to be familiar with the green roof experimental set-up. The candidate leaded with the experimental tests, the analysis of the data, as well as the writing of the scientific article.

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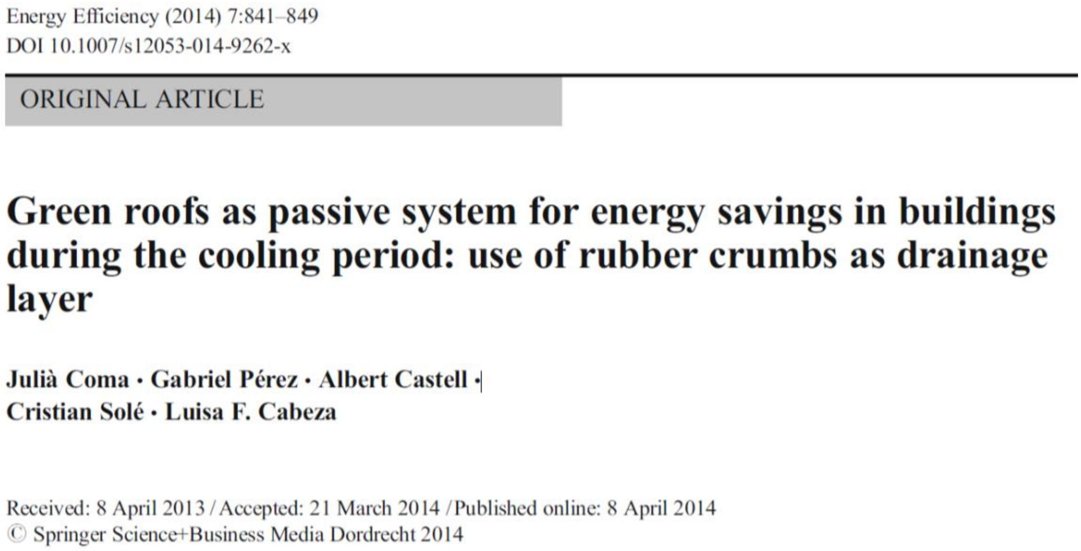
## 4.5 Journal paper



Energy Efficiency (2014) 7:841–849
DOI 10.1007/s12053-014-9262-x

ORIGINAL ARTICLE

### Green roofs as passive system for energy savings in buildings during the cooling period: use of rubber crumbs as drainage layer

**Julià Coma · Gabriel Pérez · Albert Castell ·**
**Cristian Solé · Luisa F. Cabeza**

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J. Coma, G. Pérez, A. Castell, C. Solé, L.F. Cabeza. Green roofs as passive system for energy savings in buildings during the cooling period: use of rubber crumbs as drainage layer. Energy Efficiency 2014;7:841-849.

DOI: 10.1007/s12053-014-9262-x

# 5 Thermal assessment of extensive green roofs as passive tool for energy savings in buildings

## 5.1 Introduction

It is well known that extensive green roofs provide interesting environmental benefits for buildings such like: increase the water retention capacity [1], mitigation the urban heat island effect (UHI) [2], increase the durability of internal membranes [3], storm water retention [4], etc. In addition, extensive green roofs are widely studied as passive energy saving systems for cooling proposes [5,6]. They are capable of reducing the indoor-outdoor temperature variations and decreasing the annual energy consumption of buildings [3,7] relying their final thermal performance on different factors such as the building insulation characteristics, the climate zone, the plant spices [8-10], the growing media [8,10,11], and the drainage layer properties [8,12,13].

However, the most results from those studies are from mathematical models and parametric analysis [3, 6, 8, 10, 14] while the experimental studies are much less. In addition, literature regarding heating periods (winter) is still scarce and the results are often controversial [14].

In this study two different extensive green roofs systems where the only difference between them is the drainage layer composition (pozzolana and recycled rubber crumbs, Figure 10 left) are in order to evaluate their potential as a passive tool for energy savings during summer and winter seasons.

The scope of the work was to test experimentally the thermal performance of both extensive green roofs systems under different cooling and heating requirements. An experimental set-up consisting of three house-like cubicles with identical internal volumes (2.4 x 2.4 x 2.4 m) was built in Puigverd de Lleida (Spain). The only difference between these three cubicles was the roof construction system. Two of them are made with extensive green roofs (one with pozzolana and the other one with recycled rubber crumbs as drainage layers) as shown in Figure 10 left, while a third cubicle was made with an insulated flat roof, which was used as a reference (Figure 10 right).

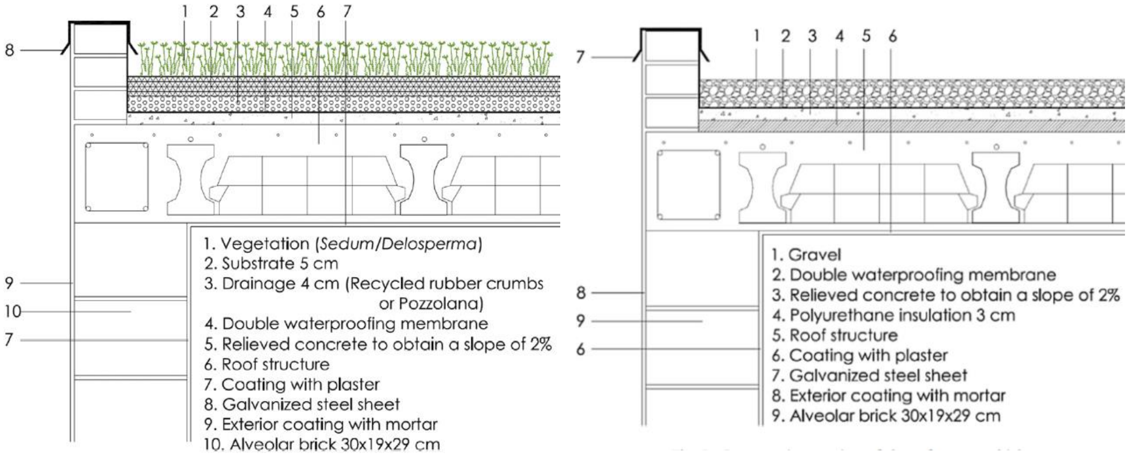

Figure 10. Construction section of green roof cubicles (left) and construction section of the reference cubicle (right)

## 5.2 Contribution to the state-of-the-art

Two extensive green roof systems without any insulation material and with 85% of the total area covered by vegetation have been experimentally tested for cooling and heating purposes. Furthermore, in order to study their potential as passive energy saving systems, a comparison with a traditional insulated flat roof was carried out. This work is presented in the following paper:

- J. Coma, G. Pérez, C. Solé, A. Castell, L.F. Cabeza. Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. Renewable Energy 2016; 85:106-1115.

This paper provides new experimental results for summer seasons thereby increasing the experimental literature as well as providing new quantitative data to enrich the scarce literature available regarding the thermal performance of extensive green roofs during winter period. In addition, the study also provides a plant development analysis throughout three years of uninterrupted experimentation, where the evolution of different plant spices and the area covered by the vegetation were discussed.

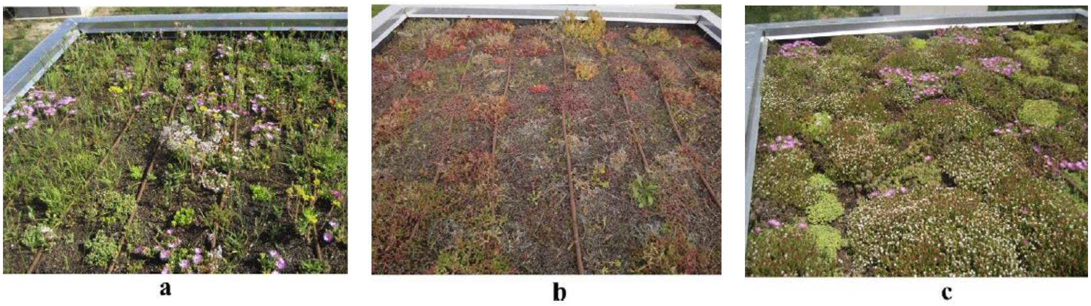

Figure 11. a) Extensive green roof. Growth phase during first summer (2011). 20% plant coverage. b) Extensive green roof. Winter view (2011-2012). c) Extensive green roof. Summer 2012 view. 85% plat coverage

The experimental results demonstrated the high potential of both green roof cubicles in reducing the electrical energy consumption of the HVAC systems of a building during the summer season. The rubber crumbs and pozzolana cubicles showed a 16.7 % and 2.2 % respectively less energy consumption in comparison to the reference cubicle during representative periods of cooling demand.

On the other hand, the results showed that during representative periods of heating, the electrical energy consumption of rubber crumbs and pozzolana cubicles increased in 6.1% and 11.1% respectively compared to the reference cubicle. After analysing the results and thermal properties for all the three constructive systems, the most dominating parameter during winter conditions seems to be thermal transmittance, which is higher for both extensive green roofs, leading to higher energy consumption.

Moreover, the better thermal performance of the green roof with rubber crumbs as drainage layer compared to the green roof with rubber crumbs was experimentally demonstrated. In addition, coherency between the results and the theoretical thermal transmittance (U-value) of both green roofs was observed.

Finally, the experimental results also highlighted the importance of both drainage and substrate layers on the overall thermal performance of these systems. Therefore, theoretical improvements for winter periods were proposed, increasing the thickness of the drainage layer from 5 cm to 8 cm to reduce the thermal transmittance of the whole green roof system and increasing the thickness of the growing media (substrate) from 5 cm to 10 or 15 cm.

## 5.3 Contribution of the candidate

The experimental test, data treatment, and analysis of the tests were the main tasks of the candidate as well as the writing of the scientific article. The co-authors collaborated along the elaboration of the paper to discuss both, the organization and the main findings of the results as well as during the answer to reviewers.

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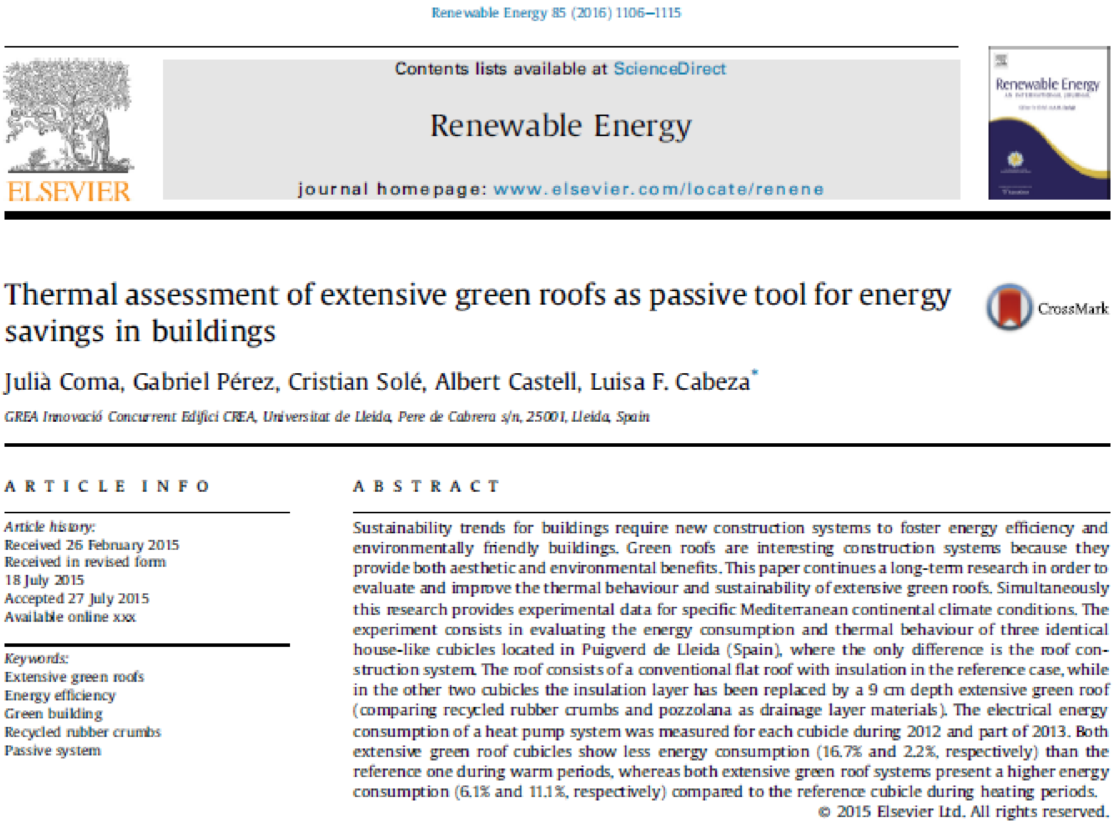
## 5.5 Journal paper



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### Thermal assessment of extensive green roofs as passive tool for energy savings in buildings

Julià Coma, Gabriel Pérez, Cristian Solé, Albert Castell, Luisa F. Cabeza*

*GREA Innovació Concurrent Edifici CREA, Universitat de Lleida, Pere de Cabrera s/n, 25001, Lleida, Spain*

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A B S T R A C T

Sustainability trends for buildings require new construction systems to foster energy efficiency and environmentally friendly buildings. Green roofs are interesting construction systems because they provide both aesthetic and environmental benefits. This paper continues a long-term research in order to evaluate and improve the thermal behaviour and sustainability of extensive green roofs. Simultaneously this research provides experimental data for specific Mediterranean continental climate conditions. The experiment consists in evaluating the energy consumption and thermal behaviour of three identical house-like cubicles located in Puigverd de Lleida (Spain), where the only difference is the roof construction system. The roof consists of a conventional flat roof with insulation in the reference case, while in the other two cubicles the insulation layer has been replaced by a 9 cm depth extensive green roof (comparing recycled rubber crumbs and pozzolana as drainage layer materials). The electrical energy consumption of a heat pump system was measured for each cubicle during 2012 and part of 2013. Both extensive green roof cubicles show less energy consumption (16.7% and 2.2%, respectively) than the reference one during warm periods, whereas both extensive green roof systems present a higher energy consumption (6.1% and 11.1%, respectively) compared to the reference cubicle during heating periods.

J. Coma, G. Pérez, C. Solé, A. Castell, L.F. Cabeza. Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. Renewable Energy 2016;85:106-1115.

DOI: 10.1016/j.renene.2015.07.074

# 6 Environmental performance of recycled rubber as drainage layer in extensive green roofs. A comparative Life Cycle Assessment

## 6.1 Introduction

During the last decade, the potential of extensive green roofs as sustainable constructive system that offers exceptional ecosystem services over traditional roof solutions in urban areas has been consolidated. The improvement of the visual environment [1], the human health [2], the mitigation of the urban heat island effect [3], the reduction of $CO_2$ concentration [4,5], the increment of the biodiversity in large cities [6] and the energy efficiency [7,8] are the most important ones.

However, the materials used in different layers of these systems are still based on conventional materials [9], which in some cases could lead to high energy consumption during the production and disposal phase of the building. According to the aforementioned, several studies [10-12] highlight the importance to replace the current green roof materials by more environmentally friendly and sustainable products.

On the other hand, some examples of Life Cycle Assessment methodologies (LCA) applied in green roofs were found in literature. However, there are still few experiences about the LCA of recycled materials and any for its use as drainage layer in extensive green roofs. Moreover, most studies use simulations to estimate the energy consumption of the building with green infrastructures during the operational phase, but there is a lack of analysis in using real data about energy consumption from experimental tests for both heating and cooling periods.

Therefore, the objective of this paper is to evaluate the environmental performance applying an LCA methodology for two new extensive green roofs where the drainage layer of one of them is made of a recycled material (rubber crumbs from used tire waste) and is compared to other one which is made of natural pozzolana (Figure 12). In addition, the LCA applied for both green roofs was compared with the LCA applied for two conventional flat roofs, with and without thermal insulation (polyurethane). For this purpose, data used for the operational phase of the LCA calculations was obtained from an experimental set-up consisting of four house-like cubicles with each type of roof, located in a Mediterranean continental climate (Puigverd de Lleida, Spain).

Figure 12. Substrate used in the extensive green roofs; left, view of the substrate over the pozzolana drainage layer, right, view of the substrate over the rubber crumbs drainage layer

## 6.2 Contribution to the state-of-the-art

In order to evaluate the potential in reducing the environmental impact of whole house-like cubicles by using two new extensive green roofs systems, this paper presents an LCA study, which is carried out based on the last impact assessment method EcoIndicator 99 [13].

- L. Rincón, J. Coma, G. Pérez, A. Castell, D. Boer, L.F. Cabeza. Environmental performance of recycled rubber as drainage layer in extensive green roofs. A comparative Life Cycle Assessment. Building and Environment 2014;74:22-30.

In the production phase the recycled rubber crumbs roof showed the highest environmental impact due to the tire dismantling process and the use of compost in the substrate. Moreover, no representative environmental differences in the construction phase of the analysed roofs were found, what lead to very similar environmental results of the four roofing systems (green roof with recycled rubber showed about 1.5% impact reduction compared to the other roofs).

On the other hand, the study verified that the operational phase was crucial in the overall results for all the studied roofs, representing about 85.7% - 87.2% of the total environmental impact. Therefore, any improvement in the energy performance of the building would lead to a lower environmental impact in the operational phase and consequently in the overall assessment. During the operational phase, the extensive green roof with recycled rubber got 7.8% impact reduction in comparison to the extensive green roof with pozzolana, 8.4% impact reduction compared to the non-insulated conventional roof, and only 2% impact increase with respect to the insulated conventional roof.

Finally, the main LCA results show that the extensive green roof with recycled rubber crumbs as drainage layer presented significant reductions in the overall environmental impact, 7% in comparison to the non-insulated conventional and 6.7% compared to the green roof with pozzolana, while has a similar environmental impact (2% increase) than an insulated conventional roof.

## 6.3 Contribution of the candidate

The candidate looked for the references and LCA standards to carry out the study and helped writing the state-of-the-art of green roofs in the introduction and the main conclusions. Moreover the "materials and methodology" section was leaded by the candidate as well as the heating and cooling tests performed in an experimental set-up, to collect and analyse all the data used in the life cycle analysis (LCA). Finally, the candidate also took part giving a deep revision and in the answer to reviewers.

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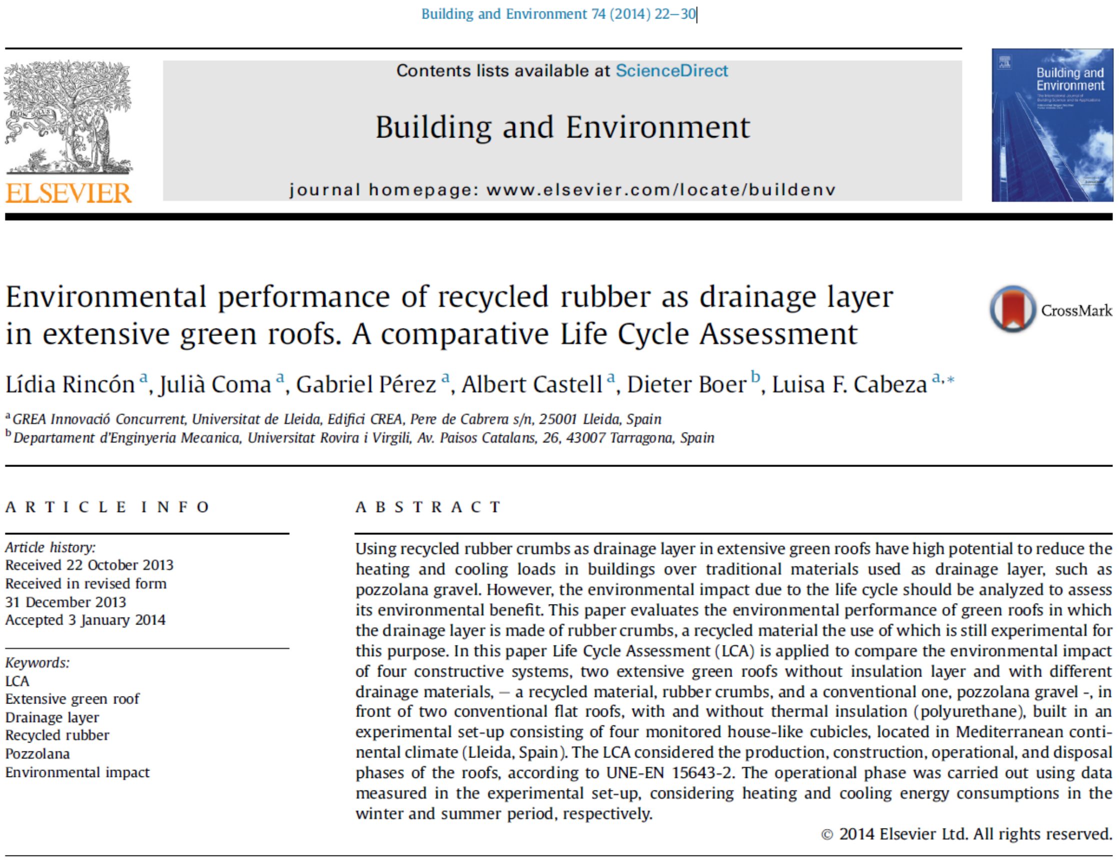

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Environmental performance of recycled rubber as drainage layer in extensive green roofs. A comparative Life Cycle Assessment

Lídia Rincón[a], Julià Coma[a], Gabriel Pérez[a], Albert Castell[a], Dieter Boer[b], Luisa F. Cabeza[a,]*

[a] *GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain*
[b] *Departament d'Enginyeria Mecanica, Universitat Rovira i Virgili, Av. Paisos Catalans, 26, 43007 Tarragona, Spain*

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ABSTRACT

Using recycled rubber crumbs as drainage layer in extensive green roofs have high potential to reduce the heating and cooling loads in buildings over traditional materials used as drainage layer, such as pozzolana gravel. However, the environmental impact due to the life cycle should be analyzed to assess its environmental benefit. This paper evaluates the environmental performance of green roofs in which the drainage layer is made of rubber crumbs, a recycled material the use of which is still experimental for this purpose. In this paper Life Cycle Assessment (LCA) is applied to compare the environmental impact of four constructive systems, two extensive green roofs without insulation layer and with different drainage materials, – a recycled material, rubber crumbs, and a conventional one, pozzolana gravel -, in front of two conventional flat roofs, with and without thermal insulation (polyurethane), built in an experimental set-up consisting of four monitored house-like cubicles, located in Mediterranean continental climate (Lleida, Spain). The LCA considered the production, construction, operational, and disposal phases of the roofs, according to UNE-EN 15643-2. The operational phase was carried out using data measured in the experimental set-up, considering heating and cooling energy consumptions in the winter and summer period, respectively.

L. Rincón, J. Coma, G. Pérez, A. Castell, D. Boer, L.F. Cabeza. Environmental performance of recycled rubber as drainage layer in extensive green roofs. A comparative Life Cycle Assessment. Building and Environment 2014;74:22-30

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# 7 Vertical Greenery Systems (VGS) for energy saving in buildings: A review

## 7.1 Introduction

As it has been highlighted in chapter one of this thesis, green infrastructures (parks, city gardens, green roofs, vertical greenery, etc.) are becoming one of the most promising systems contributing to a more sustainable development not only at building but also at urban scale. From this approach, closing the cycle of materials and water and reducing the energy demand are priority objectives [1].

Focusing on buildings, there are two ways to integrate green infrastructures. On one hand, the green roofs systems (intensive and extensive) [2], which are being studied and used for more than fifty years around the world, and on the other hand vertical greenery systems (VGS). In this case, there is some dispersion in the scarce literature regarding its classification, construction system, plant species used, climate influence, and the thermal performance when implemented in buildings. The lack of its implementation could be attributed to the economical (high initial investment) and technical points of view, where it is probably easier to use a flat space (roof) in comparison to a vertical facade, and finally due to a lack of knowledge about their performance and environmental benefits.

However, vertical systems can offer higher potential than green roofs on the building environment because the area of walls is always bigger than the area of the roof. In the case of high-rise buildings, the ratio of the walls could be 20 times the roof area [3].

## 7.2 Contribution to the state-of-the-art

In order to provide a clear overview of the vertical greenery systems and to analyse the weak spots of the current state-of-the-art, the aim of this study is to organize and summarize the existent literature concerning these systems when they are used as passive system for energy savings in buildings. The main findings of the study are presented and discussed in the following paper:

- G. Pérez, J. Coma, I. Martorell, L.F. Cabeza. Vertical Greenery Systems (VGS) for energy saving in buildings: A review. Renewable and Sustainable Energy Reviews 2014;39:139-165.

First of all, it is highly recommended establishing a classification between different VGS for buildings because unlike other building systems, such as green roofs, which are classified between extensive and intensive, there is no established standardization for VGS designs and its variations. However, according to the growing method used these systems are labelled as green facades and living walls systems by some authors [4] and organizations [5]. Moreover, the classification proposed by Pérez et al. [6] encompasses both, green facades and living walls definitions, while at the same time it connects these definitions with the extensive and intensive concepts. Thus, to better understand this review, the classification presented in the Table 4 is used along the paper.

Table 4. Classification of vertical greenery systems for buildings [6]

| | **Extensive systems** | | **Intensive systems** |
|---|---|---|---|
| **Green facades** | Traditional green facades | --- | --- |
| | Double-skin green facade or green curtain | Modular trellis | --- |
| | | Wired mesh | --- |
| | | --- | Perimeter flowerpots |
| **Living walls** | --- | --- | Panels |
| | --- | --- | Geotextile felt |

After this literature review, some key factors that influence the final thermal performance of vertical greenery systems, such as the construction system used, the type of vegetation implemented, the operation mechanisms, and finally the climate influence, are clarified. In addition, a comprehensive review and discussion sorted by construction system, simulations, and climatic situation are summarized. Finally, the paper includes a section about related literature which provides complementary information for the paper, such as the influence of VGS over urban environment, influence over indoor environments, maintenance of different systems, life cycle analysis (LCA), and sound insulation capacity.

The main outcomes concerning the thermal performance of these systems are known when applied as a passive cooling system. They can decrease the external wall surface temperature, ranging from 1 ºC and 20.8 ºC depending on the system, orientation, plant species and climate conditions, thus the energy consumption of the building from 5 to 50 %. However, a lack of data of the thermal performance during the heating periods as well as for a whole year (spring, autumn and winter) was found for all classified systems. Only one simulation study conducted by McPherson et al. [7], showed a 21 % extra energy consumption during the heating period in Madison (EE.UU.), but no VGS was specified.

Moreover, the importance of the facade orientation is relevant for energy savings, especially for cooling periods, but a lack of studies related to the performance of East and West facades is seen, because the published studies are mainly focused on the South. In addition, a world classification according to the climate conditions presented in Figure 13 showed that most of the studies are located in a warm temperate climate (C) with some exceptions in equatorial climate (A) [8]. Therefore, it is necessary to perform more studies in different climates, throughout the whole year, providing the performance for the different facade orientations.

On the other hand, other important factors that affect to the final performance of these systems, such as the evapotranspiration effect, the foliage thickness, the air gap created between the vegetation and walls (green walls and double-screen facades), wind barrier effect, and the characterization of the shadow effect by the leaf area index (LAI), must be studied in depth.

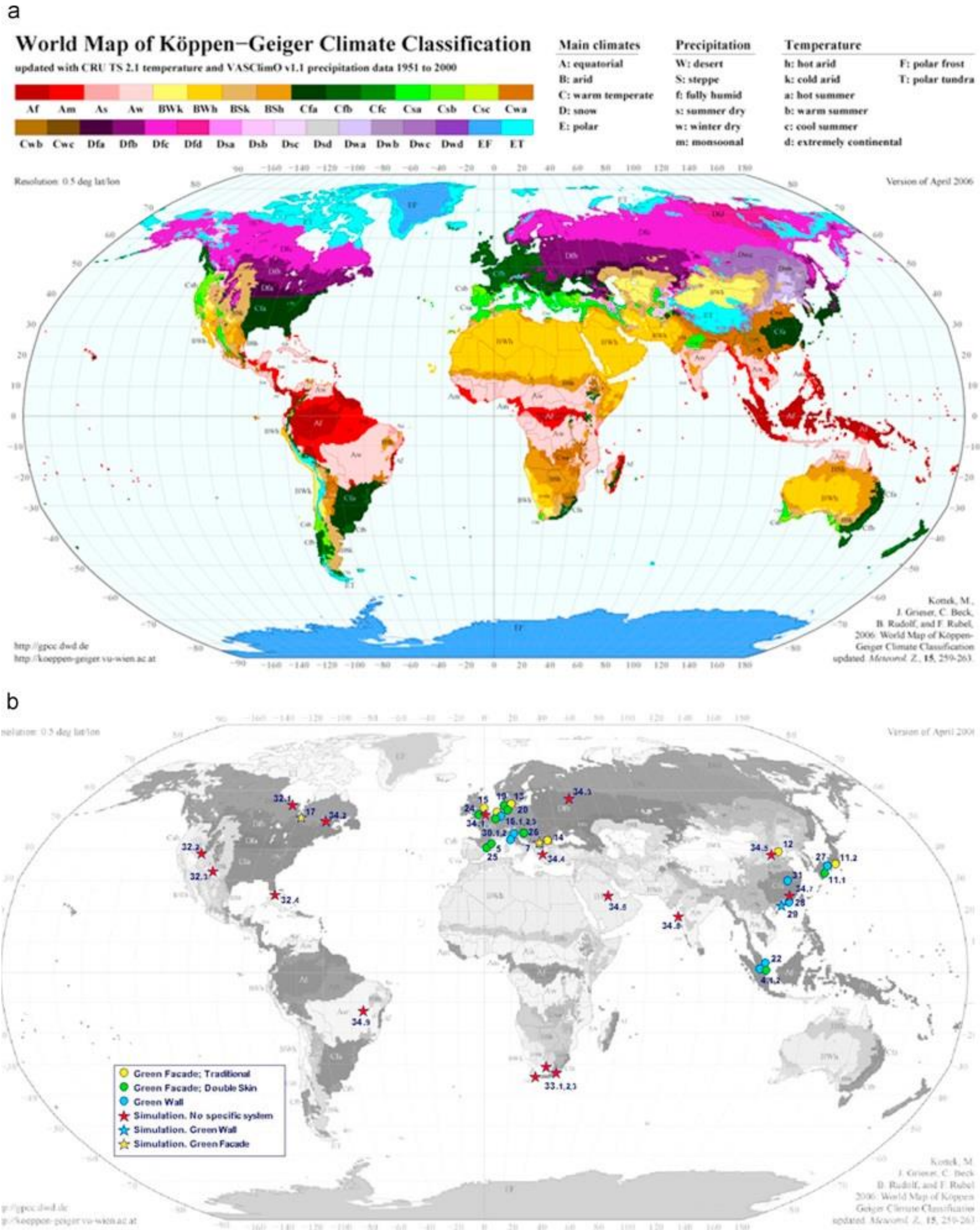

Figure 13. (a) The Köppen Climate Classification, (b) The Köppen Climate Classification and situation of analysed papers by categories

In order to show an overview of the literature review, a total of twenty-five different VGS studies about energy savings in buildings were reviewed and classified with a comprehensive discussion. Seven of them were related to traditional green facades (five case studies and two simulations). Moreover, ten studies were found regarding double-skin green facades (seven experimental and three case studies). Finally, eight green wall studies were reviewed; where five were experiments, two of them were simulations, and only one was an analysis of a real case.

Finally, the necessity to do more research on different VGS topics, such as standardization of the system classification, experiments at real scale, thermal performance analysis for both heating and cooling purposes, where the results can be compared with similar studies, different climate conditions, facade orientations, characterization of the shadow effect by leaf area index (LAI), and the air gap between green facades and building walls, is highlighted. Furthermore, other interesting fields to be studied in depth, where the aim is enhancing the buildings and their environment are the noise insulation capacity of all these systems and a comparative analysis of the life cycle between VGS and other commercial systems used for the same purpose.

## 7.3 Contribution of the candidate

The candidate contributed to the research, proposing an extended list of references to review and classify the vertical greenery when it is applied as a passive system for energy savings in buildings. Afterward the list was extended by the co-authors. Moreover, the candidate took part in the organization of the paper as well as in the redaction of vertical greenery systems for energy savings in buildings, discussion and conclusions sections. Finally, a comprehensive and deep revision of the whole paper was carried out.

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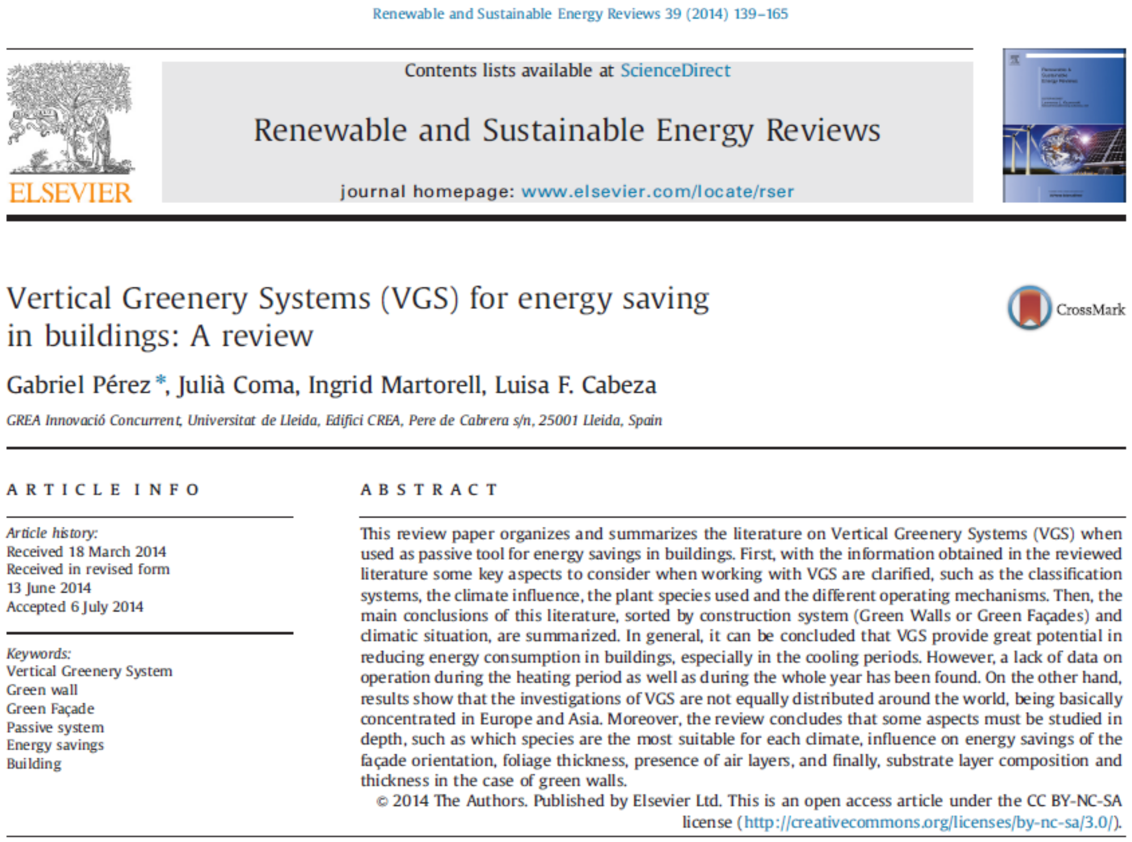
## 7.5 Journal paper



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# Vertical Greenery Systems (VGS) for energy saving in buildings: A review

Gabriel Pérez*, Julià Coma, Ingrid Martorell, Luisa F. Cabeza

*GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain*

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ABSTRACT

This review paper organizes and summarizes the literature on Vertical Greenery Systems (VGS) when used as passive tool for energy savings in buildings. First, with the information obtained in the reviewed literature some key aspects to consider when working with VGS are clarified, such as the classification systems, the climate influence, the plant species used and the different operating mechanisms. Then, the main conclusions of this literature, sorted by construction system (Green Walls or Green Façades) and climatic situation, are summarized. In general, it can be concluded that VGS provide great potential in reducing energy consumption in buildings, especially in the cooling periods. However, a lack of data on operation during the heating period as well as during the whole year has been found. On the other hand, results show that the investigations of VGS are not equally distributed around the world, being basically concentrated in Europe and Asia. Moreover, the review concludes that some aspects must be studied in depth, such as which species are the most suitable for each climate, influence on energy savings of the façade orientation, foliage thickness, presence of air layers, and finally, substrate layer composition and thickness in the case of green walls.

G. Pérez, J. Coma, I. Martorell, L.F. Cabeza. Vertical Greenery Systems (VGS) for energy saving in buildings: A review. Renewable and Sustainable Energy Reviews 2014;39:139-165.

DOI: 10.1016/j.rser.2014.07.055

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

## 8.1 Introduction

As the potential of vertical greenery systems (VGS) to provide many ecosystems services, such as energy savings in buildings, was highlighted in the previous chapter, with the aim to enrich this topic, next steps of the research were focused on filling some gaps found in the literature review [1].

Referring to the contribution of these systems as a passive tool for energy savings in buildings, this ecosystem service is essentially developed due to the shadow effect provided by the vegetation, which is a key factor as Pérez et al. stated in 2011[2]. Other important factors, but with minor magnitude, are the water transpiration from plants and the evaporation from substrates, the insulation effect from the system used (substrates, felts, air gap, panels), and finally the modification of wind influence on the building surfaces [3].

Since the shadow effect is directly related to the amount of foliage in the green facade, the relation of the leaf mass and the energy savings could be a simple way to characterize the benefit that a green facade provides at any time during its development. Being the Leaf Area Index (LAI) the most used methodology in agriculture and ecology to measure the development and yield of crops [4], also could be a useful tool to characterize the leaf mass and the consequent shadow effect of VGS in buildings.

Some previous studies [5-7] used the LAI concept to analyse the potential of VGS as a passive energy saving system in buildings, but some important issues such as the methodology to measure the LAI in these systems and the relation between LAI and energy savings provided have not yet been resolved. Likewise, further studies have to address e.g. the LAI of the different species used for VGS, the variations of LAI according to the height and the climatic influence on the plant development and its consequent LAI variations.

## 8.2 Contribution to the state-of-the-art

The main objectives of this paper were: (1) to summarize the main results of the different experiments carried out in a double-skin green facade addressed, (2) to provide an easy methodology to measure the leaf area index (LAI), and (3) to relate it to the shadow effect, as well as the energy savings provided. This work is presented in the following paper:

- G. Pérez, J. Coma, S. Sol, L.F. Cabeza. Green facade for energy savings in buildings: the influence of Leaf Area Index and facade orientation on the shadow effect. Submitted to Applied Energy 2016.

To carry out the study, two equal house-like cubicles with identical shape and materials were used. The only difference was on the East, South and West facades of one of them, where a simple lightweight steel mesh was anchored at 20 cm separated from the building wall creating an intermediate space between the Boston Ivy, which is deciduous, and the building wall (Figure 14).

Figure 14. Double-skin green facade under study made with Boston Ivy (*Parthenocissus tricuspidata*), left, summer 2013; right, summer 2015

First of all, in order to better understand the paper, the LAI concept is clarified. Thus LAI is defined as a dimensionless parameter (ranging from 0 to 10) to measure the different plant canopies (LAI = leaf area/ground area, $m^2/m^2$) [8], and can be generally measured according two methodologies, direct or indirect. On one hand, the direct method involves harvesting all the leaves of a plot and measuring the area of each leaf (Figure 15, left). On the other hand, as shown in Figure 15 right, indirect methods are based on the measurement of parameters directly related to LAI, such as the amount of light transmitted or reflected by the plant canopy [9].

Figure 15. Left, direct LAI measurements summer 2013. Right, indirect LAI measurements 2015

In this paper, both methodologies are applied in order to analyse the LAI of the double-skin green facade. The results summarized in Table 5 confirm that both methodologies provide similar values for the LAI with slightly differences because the plants evolved from 2013 to 2015 decreasing their values in the lower level and increasing in middle and upper levels.

Table 5. Comparative LAI values between intensive and extensive methods in a GF made with Boston Ivy (*Parthenocissus tricuspidata*)

| | **Direct method 2013** | **Indirect method 2015** |
|---|---|---|
| **Upper** | 2.1 | 3.3 |
| **Middle** | 3.2 | 3.5 |
| **Lower** | 3.9 | 3.4 |

Furthermore, it is interesting to highlight that the direct method is the most accurate to measure the LAI, but it requires a lot of time to harvest and measure one by one all leafs. However, the indirect method is not intrusive for the plant, being the easiest and fastest methodology to obtain LAI values from plants.

On the other hand, the shadow factor obtained during the daily solar radiation peaks in the experiments were also compared to those provided by artificial barriers (cantilevers, facade setbacks, awnings, vertical and horizontal slats, etc.), which are mainly used in buildings [10]. The results showed that a simple double-skin green facade can provide equal or better shadow factors in all the orientations in comparison to the artificial barriers above mentioned.

In addition, to study the cooling performance of the double-skin green facade, several tests under controlled temperature at 24 ºC, according the ASHRAE standards [11], were carried out. In these experiments, LAI values were related to the external wall surface temperature reductions (Figure 16) as well as with the accumulated energy consumption, which was 34% less in comparison to the reference cubicle for the same representative summer period of August 2015.

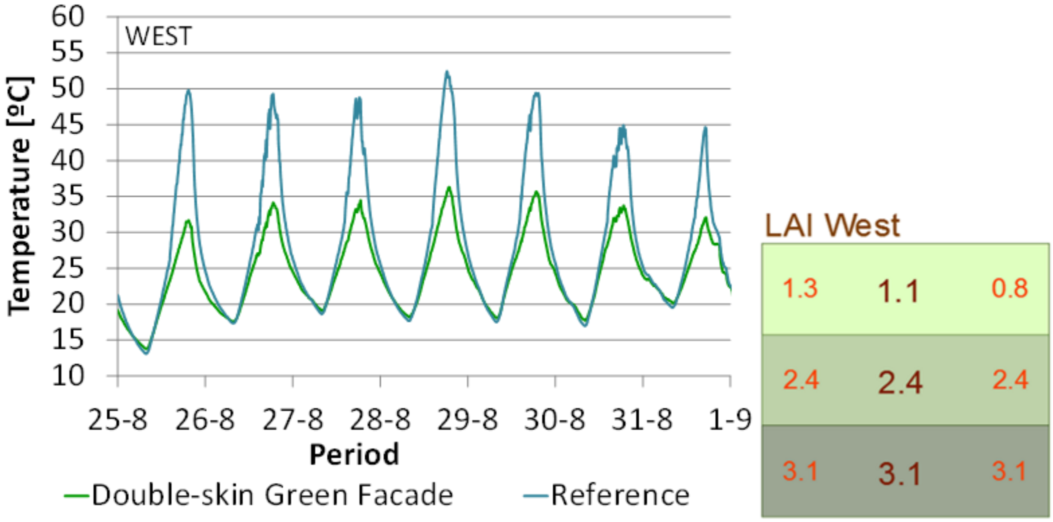

Figure 16. Evolution of external surface wall temperatures during 4th week of August 2015

## 8.3 Contribution of the candidate

The main contributions of the candidate were to perform the experimental tests and to contribute in writing some parts of the scientific paper related to the thermal performance of the system. The data treatment, the artwork, and analysis of the tests were also a task of the candidate.

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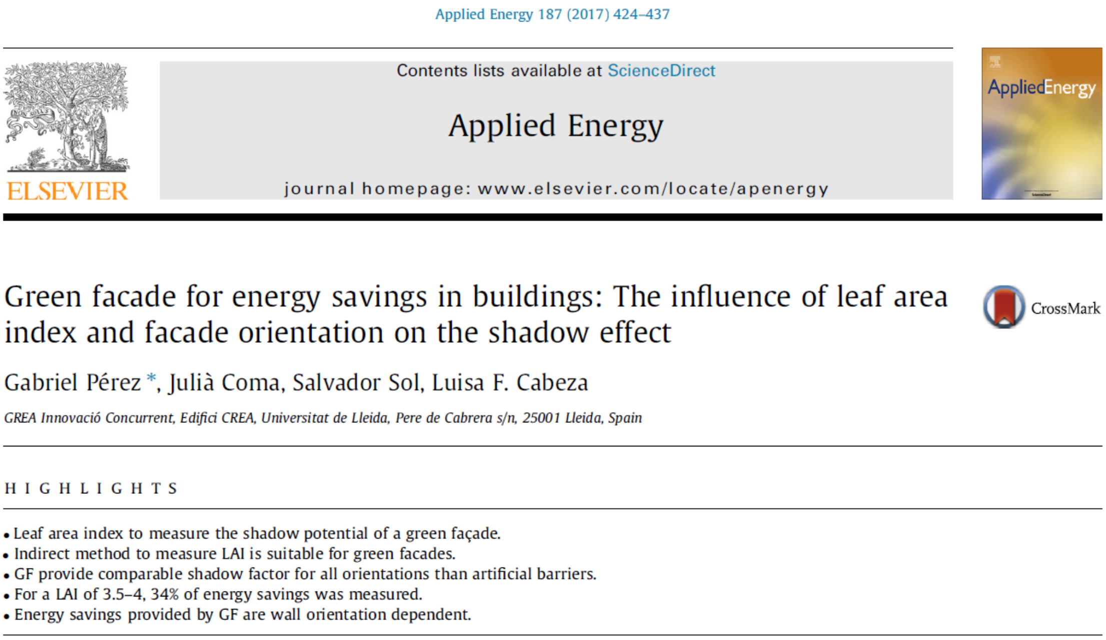
## 8.5 Journal paper



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

CrossMark

Gabriel Pérez *, Julià Coma, Salvador Sol, Luisa F. Cabeza

*GREA Innovació Concurrent, Edifici CREA, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain*

HIGHLIGHTS

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

G. Pérez, J. Coma, S. Sol, L.F. Cabeza. Green facade for energy savings in buildings: the influence of Leaf Area Index and facade orientation on the shadow effect. Submitted to Applied Energy 2016.

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# 9 Vertical Greenery Systems (VGS) for energy savings in buildings: a comparative study between green walls and green facades

## 9.1 Introduction

As it has been presented in the two previous chapters, vertical greenery systems (VGS) are one of the most potential systems to promote many ecosystem services at building and city scales, increasing biodiversity, decreasing pollution, enhancing aesthetics, as well as energy efficiency of buildings, being this last the focus of this paper [1].

Even though there are some authors that are studying the thermal performance of these systems, it is difficult to establish a technical comparison between them when critical factors such as the construction system, the climate conditions, the plant species, the foliage thickness, the air layer, the thermal performance according to the orientation of the facade, and the duration and periods of the study are considered. In addition, the construction system of the walls used in the studies is often different, fact that influences the results of energy flows through the building facade, spoiling the possibilities of comparison. None of them provides enough key factors to establish a proper comparison. A remarkable fact is that a lack of studies of the thermal performance during heating periods was observed.

Despite of the dispersion in the literature, it can be stated that one key factor to compare the potential as passive energy saving systems for all of these studies is the reduction of the building wall surface temperature due to the combined effects provided by the vertical greenery system, as it was concluded by Pérez et al. 2014 [2].

Further studies to obtain experimental data from VGS in different climates under the above mentioned defined critical factors would allow a comparison between the systems, quantifying the building wall surface temperature reductions as well as the energy savings in order to help architects and engineers to make more appropriate decisions in the design phase of buildings.

## 9.2 Contribution to the state-of-the-art

First of all and as already pointed out, a clear classification to be able to compare VGS regarding energy efficiency in buildings was missing. Therefore, the most significant previous experimental studies on the use of VGS as passive tool for energy savings in buildings are reviewed and sorted by construction system.

The main objectives of this paper were: (1) to provide an overview of the main findings in the state-of-the-art regarding the energy efficiency of VGS in buildings, (2) to characterize the thermal performance of two different VGS (double-skin green facade and living wall or green wall) for cooling and heating purposes, (3) to compare the energy consumption of each system with the reference one, and (4) to analyse the influence of facade orientation on the thermal performance of these systems. All the studies conducted to achieve these objectives were done under Mediterranean continental climate conditions. The experimental results and details about this research are presented in:

- J. Coma, G. Pérez, A. de Gracia, S. Burés, M. Urrestarazu, L.F. Cabeza. Vertical Greenery Systems (VGS) for energy savings in buildings: a comparative study between green walls and green facades. Submitted to Building and Environment, 2016.

The experimentation presented in the paper shows the performance of three house-like cubicles with the same wall and roof construction systems and the same dimensions. The difference between them is that one of them has no greenery on the facades (REF), another has a double-skin green facade (GF) on the East, South and West facades, and the last one has living wall or green wall (GW) on the same three facades as shown in Figure 17.

Figure 17. Studied cubicles in the experimental set-up in Puigverd de Lleida. From left to right: Reference, Double-skin green facade, and Green wall

Two different types of experiments were performed: “free floating”, without any cooling device where no HVAC system was used, and “controlled temperature”, where a set point temperature in the heat pump was established.

After performing several experiments during Summer 2015 with an internal controlled temperature at 24 ºC, both GW and GF cubicles showed the big potential of the VGS as a passive tool for cooling purposes in buildings, obtaining energy savings up to 58.94 % and 33.83 %, respectively, in comparison to the reference cubicle.

To better understand the energy savings in both VGS, the hourly energy consumed by each cubicle and the solar irradiance are shown in Figure 18. Furthermore, a direct relation between solar irradiation and energy savings was found indicating higher energy savings potential in climates with high solar irradiance. The experimental analysis highlights the importance of the shade effect to control this ecosystem service.

Experiments without HVAC systems were performed during Summer 2015, supplying useful information to compare the shadow effect provided by the vegetation on different facade orientations. The main results showed interesting temperature reductions on East, South and West facades being 17.0 ºC, 21.5 ºC and 20.1 ºC, respectively, for the GW cubicle, and 13.8 ºC, 10.7 ºC and 13.9 ºC, respectively, for the GF cubicle.

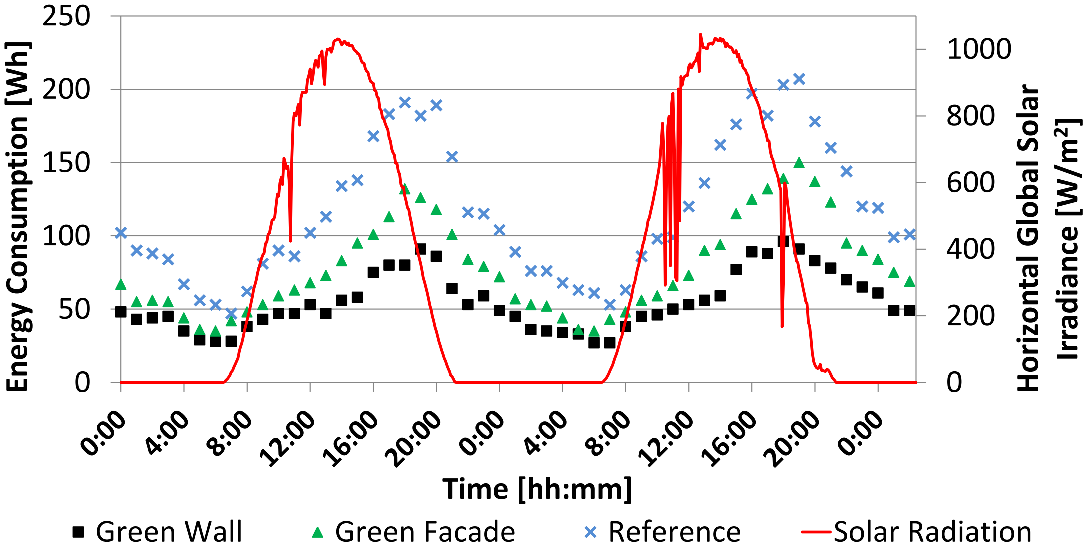

Figure 18. Hourly electrical energy consumption (6 and 7 July 2015). Controlled temperature at 24 ºC (cooling)

On the other hand, the performed experiments for winter were studied considering a comfort set point of 22 ºC. The double-skin green facade cubicle (GF) with deciduous plants, as it do not intercepts the solar radiation because the lack of foliage during winter period, showed the same energy consumption than the reference cubicle, whereas the evergreen GW showed an interesting reduction of 4.2 % of energy demand. That fact could be attributed to the night radiative protection (insulation effect) supplied by the vertical recycled polyethylene modules filled with substrate that are part of the construction system. This is a remarkable and promising finding which must be studied in depth to improve the thermal performance of GW during the whole year.

## 9.3 Contribution of the candidate

The candidate led the long term experimental research, the analysis of the tests, the figures presented as well as the writing of the scientific article. The sensors installation, the data registration connection and the monitoring of both VGS was also carried out by the candidate. On the other hand, the co-authors contributed to write some parts of the introduction and to provide a comprehensive discussion, dissertation of the results and a deep review of the whole paper. Also the candidate was supported by the co-authors to build the experimental set-up presented.

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## 9.5 Journal paper

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

CrossMark

Julià Coma [a], Gabriel Pérez [a, *], Alvaro de Gracia [b], Silvia Burés [c], Miguel Urrestarazu [d], Luisa F. Cabeza [a]

[a] GREA Innovació Concurrent, Edifici CREA, Universitat de Lleida, Pere de Cabrera s/n, 25001, Lleida, Spain
[b] Departament d'Enginyeria Mecanica, Universitat Rovira i Virgili, Av. Països Catalans 26, 7 43007, Tarragona, Spain
[c] Buresinnova S.A., Barcelona, Spain
[d] Departamento de Agronomía, Universidad de Almería, Almería, 04120, Spain

J. Coma, G. Pérez, A. de Gracia, S. Burés, M. Urrestarazu, L.F. Cabeza. Vertical Greenery Systems (VGS) for energy savings in buildings: a comparative study between green walls and green facades. Submitted to Building and Environment 2016.

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# 10 Acoustic insulation capacity of Vertical Greenery Systems for buildings

## 10.1 Introduction

Nowadays, green infrastructure (GI) is a successfully tested tool, which provides ecological, economic and social benefits using natural solutions in the built environment, also known as urban ecosystem services. As John W. Dover stated in his book [1], these multiple benefits are sorted by the services that they provide to the humans and wildlife such us visual amenities, human health, food production, climate control, biodiversity, energy efficiency in buildings, and pollution control.

Several of the abovementioned urban ecosystems services delivered by the vegetation in buildings have been studied throughout the last decades. In the case of energy efficiency in buildings, most of the main gaps found in the literature [2] are addressed in the previous chapters of this thesis. However, other ecosystem services such like pollution control are still scarcely studied. In this regard, the main attributes of the pollution control ecosystem service are water resources, light, air pollution, and noise reduction, being the last, one of the main attributes of VGS to be addressed for buildings [1].

In the literature, some authors [3,4] highlight the contribution of VGS and green roofs on the reduction of noise. Nevertheless, few case studies and even less experimental data were found [5,6]. From these previous studies, no strong conclusions were established due to both, the different experimental methodologies and construction systems evaluated. Furthermore, it is interesting to point out that only one in-situ experiment was found, being the others laboratory studies with small samples or simulations [7].

## 10.2 Contribution to the state-of-the-art

The main objectives of this paper are to provide a literature review of the acoustic insulation capacity of vertical greenery systems, and to provide in-situ measurements from two different VGS, double-skin green facade (extensive system) and living wall or green wall (intensive system). Two main comparisons were carried out: to compare the noise reduction due to the existence of vegetation in each system, and to establish a comparison between both systems in terms of noise reduction. This work is presented in the following paper:

- G. Pérez, J. Coma, C. Barreneche, A. de Gracia, M. Ufrrestarazu, S. Burés, L.F. Cabeza. Acoustic insulation capacity of Vertical Greenery Systems for buildings. Applied Acoustics 2016;110:218-226.

In order to study the acoustic insulation potential of these two VGS the standard *UNE-EN ISO 140-5 Acoustics, measurement of sound insulation in buildings and of building elements, part 5: Field measurements of airborne sound insulation of facade elements and facades* was followed.

First of all, to quantify the acoustic performance of the vegetation, two different measurement periods was established. The first was carried out with low vegetation conditions and the second measurement was performed when the vegetation was completely developed as shown in Figure 19.

Figure 19. In situ acoustic measurements according to UNE-EN ISO 140-5

The main results obtained after comparing low and high values of vegetation, highlighted the differences between the double-skin green facade (GF) and green wall (GW) systems. The importance of substrate contribution to noise attenuation in the GW allowed developing a constant noise profile along the frequency spectrum tested in both measured periods, whereas GF showed a much more irregular profile (Figure 20). In addition, the improvement of the acoustic insulation capacity from both greenery systems provided by plants (scattering) in high frequencies, as well as from substrate (absorption) in the middle frequencies by Green Wall, were verified in the standardized difference of levels profiles.

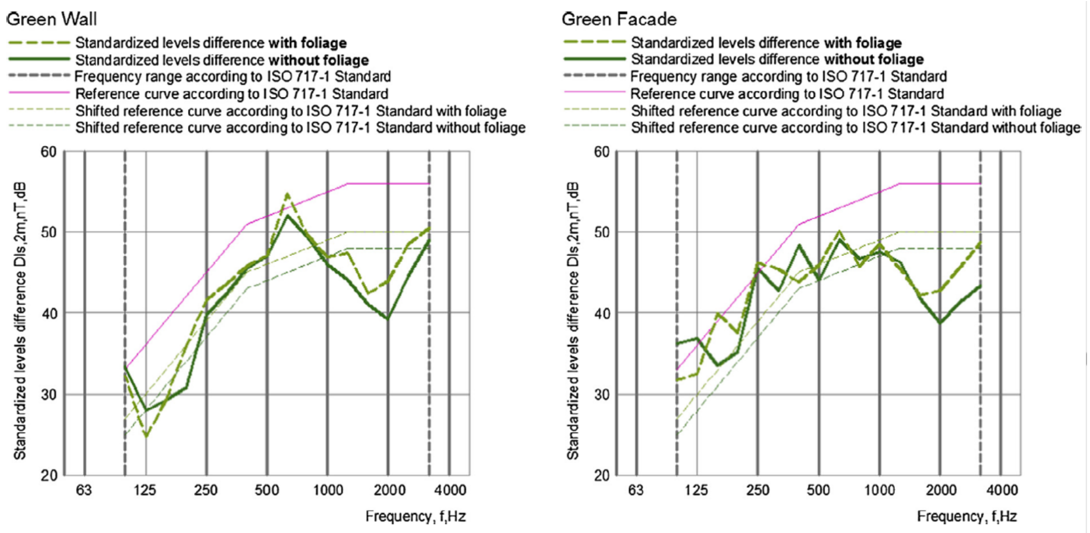

Figure 20. Standardized difference of levels D2m,nT. Green Wall vs Green Facade

Moreover, to better understand the noise insulation capacity of these systems, the study provides the value used (single-number quantity) to express the acoustic insulation between a room and the outdoor conditions. In Table 6 the main results are summarized (refer to paper to see how corrected values are calculated).

Table 6. Standardized levels difference (D2m,nT,w) [dB]. Single-number quantities

| | | **$D_{2m,nT}$ [dB]** | **Corrected value to pink noise [dB]** | **Corrected value to traffic noise [dB]** |
|---|---|---|---|---|
| With foliage | Green facade | 46 | 45 | 43 |
| | Green wall | 46 | 44 | 41 |
| Without foliage | Green facade | 44 | 42 | 42 |
| | Green wall | 44 | 42 | 40 |

Regarding the noise insulation capacity against the outdoor influences at low frequencies (≤315 Hz, aircrafts, urban traffic, railway traffic at low speeds, disco music or certain industrial noises), the cubicle with green wall presents smaller sound insulation (41 dB) in comparison with the double-skin green facade (43 dB).

In quantitative terms, a thin layer of vegetation (20–30 cm) was able to provide an increase in the sound insulation of 1 dB for traffic noise (in both, green wall and green facade), and an insulation increase between 2 dB (Green Wall) to 3 dB (Green Facade) for a pink noise.

The study highlight the necessity to consider other factors, in addition to the vegetation, in order to improve the acoustic insulation capacity of VGS, such as the mass (thickness and composition of the substrate and vegetation layers), impenetrability (sealing joints between modules) and structural insulation (support structure).

## 10.3 Contribution of the candidate

The list of references purposed, which after were extended by the co-authors, the writing of several parts of the scientific paper and the control and maintenance throughout experimental tests from 2013 to 2016, were the main contributions of the candidate. Also, the candidate took part in the organization of the paper, in the analysis and discussion of the results, along with the co-authors.

## 10.4 References

1. John W. Dover. Green Infrastructure: Incorporating plants and enhancing biodiversity in buildings and urban environments. ISBN 978-0-415-5213-9. Routledge, 2015.

2. G. Pérez, J. Coma, I. Martorell, L.F. Cabeza. Vertical Greenery Systems (VGS) for energy saving in buildings: a review. Renewable and Sustainable Energy Reviews 2014;39:139-165.
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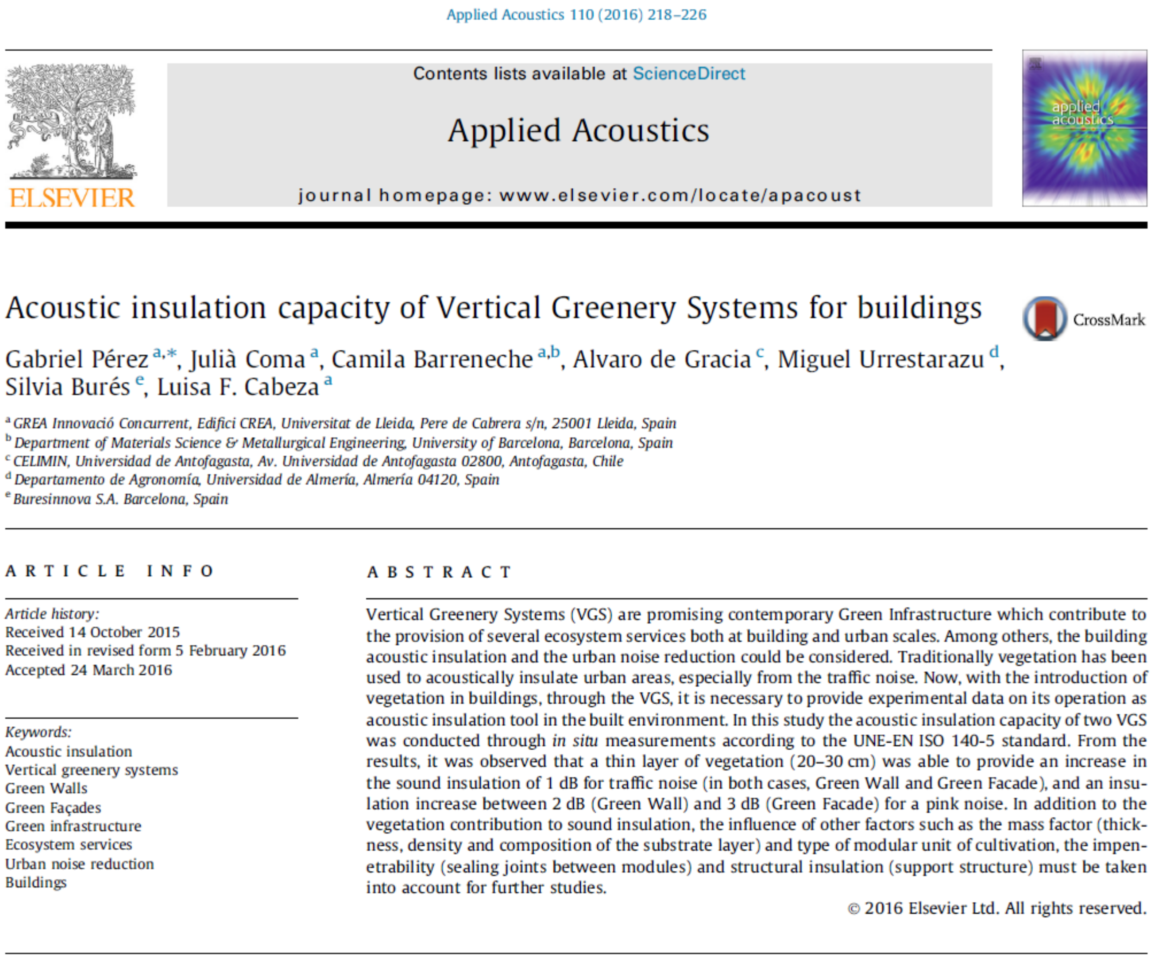
## 10.5 Journal paper



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# Acoustic insulation capacity of Vertical Greenery Systems for buildings

Gabriel Pérez [a],*, Julià Coma [a], Camila Barreneche [a,b], Alvaro de Gracia [c], Miguel Urrestarazu [d], Silvia Burés [e], Luisa F. Cabeza [a]

[a] GREA Innovació Concurrent, Edifici CREA, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain
[b] Department of Materials Science & Metallurgical Engineering, University of Barcelona, Barcelona, Spain
[c] CELIMIN, Universidad de Antofagasta, Av. Universidad de Antofagasta 02800, Antofagasta, Chile
[d] Departamento de Agronomía, Universidad de Almería, Almería 04120, Spain
[e] Buresinnova S.A. Barcelona, Spain

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ABSTRACT

Vertical Greenery Systems (VGS) are promising contemporary Green Infrastructure which contribute to the provision of several ecosystem services both at building and urban scales. Among others, the building acoustic insulation and the urban noise reduction could be considered. Traditionally vegetation has been used to acoustically insulate urban areas, especially from the traffic noise. Now, with the introduction of vegetation in buildings, through the VGS, it is necessary to provide experimental data on its operation as acoustic insulation tool in the built environment. In this study the acoustic insulation capacity of two VGS was conducted through *in situ* measurements according to the UNE-EN ISO 140-5 standard. From the results, it was observed that a thin layer of vegetation (20–30 cm) was able to provide an increase in the sound insulation of 1 dB for traffic noise (in both cases, Green Wall and Green Facade), and an insulation increase between 2 dB (Green Wall) and 3 dB (Green Facade) for a pink noise. In addition to the vegetation contribution to sound insulation, the influence of other factors such as the mass factor (thickness, density and composition of the substrate layer) and type of modular unit of cultivation, the impenetrability (sealing joints between modules) and structural insulation (support structure) must be taken into account for further studies.

G. Pérez, J. Coma, C. Barreneche, A. de Gracia, M. Urrestarazu, S. Burés, L.F. Cabeza. Acoustic insulation capacity of Vertical Greenery Systems for buildings. Applied Acoustics 2016;110:218-226.

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# 11 Conclusions and recommendations for future work

## 11.1 Conclusions of the thesis

This PhD thesis studied two of the ecosystem services provided by the most common green infrastructures when are applied in buildings, on one hand the energy efficiency of extensive green roofs and vertical greenery systems, and on the other hand the sound insulation capacity provided by VGS. In spite of providing quantitative experimental data to address the lack of information in the literature, this thesis also focused on analysing the environmental impact of extensive green roofs in order to study their sustainability.

The main accomplishments of this PhD are the following:

- The literature reviewed about green infrastructures in buildings highlighted the extended research done in the green roofs topic, whereas scarce literature is available for VGS. This fact pointed out the novelty of this topic and the necessity to develop new research, since VGS implemented in buildings not only provide aesthetics, but also supply many benefits to the built environment.
- In general, the experimental studies have demonstrated the potential of both, extensive green roofs and VGS, to reduce the cooling demand in a building in summer.

The main conclusions obtained after performing long-term experimental tests for both non-insulated extensive green roofs with two different drainage layers (pozzolana and rubber crumbs) in the facility of Puigverd de Lleida, are listed below:

- Both extensive green roofs without insulation layer demonstrated their potential as passive systems during the summer season, even when only the 20% of the roof area was covered by vegetation. The same thermal behaviour was observed when vegetation was completely developed (85% roof covered), showing 2.2 to 16.7 % energy savings in comparison to the reference roof.

- The substrate and drainage layers have important roles in the overall thermal performance of green roof system, especially when the vegetation is scarce during the first year after its installation.
- The set of experiments performed without HVAC systems, demonstrated that both extensive green roofs provided significant reductions (1.5 ºC) in internal ceiling temperatures, in comparison to the reference one.
- In winter, the thermal inertia provided by extensive green roofs, is not useful in preventing energy losses, since the external air temperature variations between day and night were below the desired internal comfort temperature.
- Several limitations in relation to the thermal performance of extensive green roofs in winter indicate that they are extremely dependent on the climate when an insulation layer is not used.
- Consequently, the experimental results of a severe winter highlighted that a 9 cm extensive green roof system has not enough thermal resistance to provide energy savings in a building. Thereby, the electrical energy consumption of the heating system was increased by 11% in pozzolana roof and 5% in rubber crumbs roof.
- In addition, the experiments carried out when the vegetation was completely developed, have demonstrated the better thermal performance of the rubber crumbs layer in comparison to the pozzolana layer for both summer and winter conditions.

Moreover, an environmental performance of extensive green roofs systems was carried out by a life cycle analysis (LCA) methodology, and the following conclusions are drawn:

- The LCA study demonstrated that the extensive green roof with rubber crumbs reduces by 7% the overall environmental impact compared to a non-insulated conventional roof, 6.7% compared to the green roof with pozzolana, and showed a similar environmental impact (2% increase), in comparison to the insulated conventional roof.

- The results confirm that the operational phase is crucial in the overall impact, being 85.7% to 87.2% of the total. Therefore, any improvement of the energy performance due to the roof system, would led to a lower overall environmental impact.

Following the structure of this thesis, the main conclusions extracted from the literature review of the VGS when are used as passive energy saving systems, are the following:

- After conducting a literature review, a disparity in the VGS nomenclature was found. Thus, an international classification of the different types of VGS to allow technical comparisons between them is highly recommended.
- Regarding the global location of VGS research, many studies were generally found in Europe and Asia, while a lack of studies in areas of the world with high solar radiation where VGS could be much more effective, were found.
- The external wall temperature reduction is the only parameter which allows a thermal performance comparison between the different types of VGS.
- For this reason, a minimum set of parameters such as the type of system and plants used, climate conditions, season, orientation of the studied facade, external wall surface reductions, air layer, and the foliage thickness should be delivered in future studies in order to establish better comparisons between different systems available in the market.
- Future VGS designs need to be developed from thermal, sustainable and acoustic engineering approaches instead of only for aesthetics or “gardening-landscaping a building”.

Finally, the main conclusions obtained after performing long-term experimental tests for both VGS (green wall and double-skin green facade) in the facility of Puigverd de Lleida, are listed below:

- The experimental studies demonstrated the high potential of GW and GF systems in reducing the electrical energy consumption of the HVAC system of a building during the summer season. These passive savings are dependent on one hand to the solar irradiation, and on the other hand to the shadow factor supplied by the typology of vertical greenery system. In Mediterranean continental climate conditions, GW and GF systems showed 58% and 33% energy savings, respectively.

- A direct relation between energy savings and the solar irradiance on the building facades was observed for both GW and GF systems. The higher the solar radiation, the higher the VGS cooling effect.
- In all the set of experiments performed in summer, the air gaps between building walls and green skins of GW showed an average temperature of 6 ºC cooler than GF system during daytimes, which demonstrates the better cooling performance of GW in comparison to GF.
- The study of the thermal performance by facade orientation in summer conditions has demonstrated that huge temperature reductions on external walls, ranging from 10.7 ºC to 13.9 in GF, and from 17 ºC to 21.5 ºC in GW, were obtained.
- The experimental studies in winter pointed out a promising radiative insulation effect during the night time provided by the GW system on the building that accounted up to 4% energy savings in a Mediterranean continental climate.
- A better thermal performance of the intensive GW compared to the extensive GF, was demonstrated for summer and winter seasons.
- A suitable indirect methodology to measure the leaf area index (LAI) on vertical surfaces was established.
- A relation between LAI factor and temperature reduction on external walls and energy savings, was found, resulting accumulated electrical energy savings up to 34% for cooling periods with a LAI of 3.5 to 4 during summer period, using a Boston Ivy (*Parthenocissus tricuspidata*) under Mediterranean continental climate.
- The acoustic experimental “in situ” measurements have demonstrated that a thin layer of vegetation (20–30 cm) was able to provide an increase in the sound insulation of 1 dB for traffic noise (in both cases, GW and GF), and an insulation increase between 2 dB (GW) to 3 dB (GF) for a pink noise.

## 11.2 Recommendations for future work

From the research presented in this thesis, quantitative data and new studies that increase the knowledge in the building GI topic have been provided. However, during the experimental part of the thesis, technical aspects that can improve the thermal performance, the sustainability and the sound insulation capacity of these systems were observed. Furthermore, many research topics in relation to green infrastructures in buildings are still waiting to be addressed. In the following section, several recommendations for further research are presented divided in green roofs and VGS.

### 11.2.1 Green roofs

- The low thermal resistance observed in the current design of the extensive green roofs limits their performance during winter. By means slightly increasing the drainage layer quickly improvements could be achieved for this purpose without compromise the sustainability of the whole system if recycled materials e.g. rubber crumbs can be used.
- The thermal performance of the whole GR system can vary depending on the vegetation density, the substrate composition and its thermos-physical properties (the lower the vegetation density, the higher the substrate contribution to the total system performance). Regarding this topic, only three studies concerning the thermos-physical characterization of substrates varying their composition and moisture content were detected.
- Regarding the environmental impact of these systems, a future LCA should consider the benefit of carbon mitigation by plants in the operational phase, since it would show a more accurate and realistic analysis.

### 11.2.2 Vertical greenery systems

- Studies about suitable plants to be installed in VGS are still scarce, and are manly focused on few species. Better knowledge of what species could be used for a determined climate conditions, sorted by LAI value, shadow factor, water requirements, climbing capacity, etc., is necessary.

- LCA analysis to compare the environmental impact between intensive and extensive VGS using experimental data is suggested. In addition, a comparison between these systems among other technologies used with the same aim, such as ventilated facades with and without PCM, horizontal and vertical slats, etc., could provide an interesting overview for engineers, architects and householders to select the best option from an environmental point of view.
- Regarding to the acoustic insulation contribution of VGS, studies regarding to the types of plants, the thickness of the vegetation layer, the thickness and composition of the substrate layer, the type of support structure and materials to be used, as well as to take measures to prevent transmission of sound on the early design phase (structural impenetrability and insulation) should be made.
- With the aim to quantify and compare the benefits provided by green infrastructures on building envelopes between different studies in a fast and simple manner, as well as to help engineers and architects in taking decisions thought the design phase, more research concerning indirect measurements of the leaf density (e.g. LAI, scanner 3D, etc.) should be carried out.

# 12 Other research activities

## 12.1 Other publications

Other scientific research about green roofs and vertical greenery systems was carried out during the execution of this thesis. The resulting publications are listed below:

- G. Pérez, A. Vila, C. Solé, **J. Coma**, A. Castell, L. F. Cabeza. The thermal behaviour of extensive green roofs under low plant coverage conditions. Energy Efficiency 2015;8(5):881-894.
- P. Bevilacqua, **J. Coma**, G. Pérez, C. Chocarro, A. Juárez, C. Solé, M. De Simone, L.F. Cabeza. Plant cover and floristic composition effect on thermal behaviour of extensive green roofs. Building and Environment 2015;92:305-316.
- Z. Azkorra, G. Pérez, **J. Coma**, L.F. Cabeza, S. Bures, J.E. Álvaro, A. Erkoreka, M. Urrestarazu. Evaluation of green walls as a passive acoustic insulation system for buildings. Applied Acoustics 2015;89:45-56.

## 12.2 Contributions to international conferences

The PhD candidate also contributed to some international conferences:

- G. Pérez**, J. Coma**, A. Vila, C. Solé, A. Castell, L.F. Cabeza. Green roofs as passive system for energy savings in Mediterranean Continental climate when using rubber crumbs as drainage layer. Innostock 2012 - The 12th International Conference on Energy Storage, Lleida (Spain).
- G. Pérez, **J. Coma**, A. Vila, C. Solé, A. Castell, L.F Cabeza. Green facades as passive systems for energy savings in Mediterranean Continental climate. Innostock 2012 - The 12th International Conference on Energy Storage, Lleida (Spain).
- **J. Coma**, G. Pérez, L.F Cabeza. Cubiertas verdes extensivas como sistema pasivo de ahorro de energía en edificios: uso de granza de caucho reciclado en la capa drenante. XV Congreso Ibérico y X Congreso Iberoamericano de Energía Solar - CIES 2012, Vigo (Spain).

- G. Pérez, **J. Coma,** C. Solé, A. Castell, L.F. Cabeza. Green roofs as passive system for energy savings when using rubber crumbs as drainage layer. SHC 2012 - International Conference on Solar Heating and Cooling for Buildings and Industry, San Francisco (USA).
- G. Pérez, **J. Coma,** I. Martorell, L.F Cabeza. Experimental results of energy measurements in green roofs and green facades in Mediterranean continental climate. COINVEDI - 2nd International Conference on Construction and Building Research 2012, Valencia (Spain).
- G. Pérez, **J. Coma,** C. Solé, L.F. Cabeza. Experimental evaluation of the 'ecological roof' in Mediterranean continental climate. Eurosun 2012, Rijeka (Croatia).
- G. Pérez, **J. Coma,** A. Castell, C. Solé, L.F. Cabeza. La vegetación de edificios como sistema pasivo de ahorro energético. III Jornadas Low Tech UPC, 2012, Barcelona (Spain).
- L. Rincón, **J. Coma,** G. Pérez, A. Castell, D. Boer, L.F. Cabeza. Comparative Life Cycle Assessment of extensive green roofs with recycled rubber or pozzolana as drainage layer. Sustainable Energy Storage in Buildings - the 2nd IC-SES 2013, Dublín (Ireland).
- **J. Coma,** G. Pérez, C. Solé, A. Castell, L.F. Cabeza. Extensive green roofs as passive system for energy savings in buildings when using rubber crumbs as drainage layer. The Fifth International Conference on Applied Energy (ICAE 2013), Pretoria (South-Africa).
- **J. Coma,** G. Pérez, C. Solé, A. Castell, L.F. Cabeza. New green facades as passive systems for energy savings on buildings. ISES SOLAR WORLD CONGRESS 2013, Cancun (Mexico).
- **J. Coma**, P. Bevilacqua, M. de Simone, G. Pérez, L.F. Cabeza. Green roofs for building energy savings. A comparative study. Eurotherm Seminar #99 - Advances in Thermal Energy Storage 2014, Lleida (Spain).
- **J. Coma**, P. Bevilacqua, M. de Simone, A. de Gracia, G. Pérez, L.F. Cabeza. Thermal characterisation of different materials for extensive green roofs. Eurotherm Seminar #99 - Advances in Thermal Energy Storage 2014, Lleida (Spain).

- **J. Coma,** G. Pérez, C. Solé, A. Castell, L.F. Cabeza. Vertical Greenery Systems (VGS) for energy savings in buildings. International Green Wall Conference 2014, Stock-on-Trent (U.K).
- **J. Coma,** G. Pérez, L.F. Cabeza. Green infrastructure improvements for a more sustainable building sector. World SB14 Barcelona. Sustainable Building: Results... Are we moving as quickly as we should? It's up to us! 2014, Barcelona (Spain).
- **J. Coma**, P. Bevilacqua, M. de Simone, A. de Gracia, G. Pérez, L.F. Cabeza. Thermal characterization of different materials for extensive green roofs. EuroSun 2014 - International Conference of Solar Energy and Buldings, Aix-les-Bains (France).
- **J. Coma**, A. de Gracia, G. Pérez, L.F. Cabeza. Thermal characterization of different materials for extensive green roofs. GREENSTOCK 2015 - The 13th International Conference on Energy Storage, Beijing (China).
- **J. Coma,** G. Pérez, L.F. Cabeza. Vertical greenery systems (VGS) as passive tool for energy savings and acoustic insulation in buildings. International Conference on Living Walls and Ecosystem Services 6-8th July 2015 University of Greenwich, London (U.K).

## 12.3 Scientific foreign-exchange

The PhD candidate did three research stays abroad during the realization of this thesis.

### 12.3.1 University of Calabria (Cosenza, Italy)

The Department of Mechanical, Energy and Management Engineering has a strategic landmark of the University of Calabria for teaching, research and technology transfer in the field of Building and Industrial Engineering. During the three month period in this department, under the supervision of Dr. Marilena De Simone, the candidate developed research activities on Green roofs for energy savings in buildings in two different main topics. On one hand, to perform a technical comparison between six different extensive green roofs systems, and on the other hand to determine experimentally the thermophysical properties of eight different substrates from the internal layers of extensive green roofs.

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### 12.3.2 University of Greenwich (Gillinham, United Kingdom)

The candidate worked on a design and implementation of a green roof monitoring system, in the Water & Environmental Management Faculty of Engineering & Science in University of Greenwich during three month supervised by Dr.Alejandro Dussaillant-Jones. The main work was to provide technical support in a green roof project in order to measure the evapotranspiration effect in an extensive green roof. The experimental study took place in a new building constructed in the southern part of the city of London in 2013, located exactly below Thames River on a Stockwell Building.

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### 12.3.3 University of South Australia (Adelaide, Australia)

PhD candidate Julià Coma has done a research in the field of building applications. He has been collaborating advised by Prof. Dr. Frank Bruno and Dr. Martin Belusko to do a state-of-the-art comparing the embodied energy of two different energy storage systems and to study the potential of vertical greenery systems as a tool to reduce the heat waves effect during summer periods.

University of
South Australia

## 12.4 Others activities

### 12.4.1 Book chapters participation

- G. Pérez, **J. Coma**, L.F. Cabeza. Green Building and Phase Change Materials: Characteristics, Energy Implications and Environmental Impacts. Green roofs and green facades for energy savings in buildings. Nova Science Publishers, Inc. 2015.

### 12.4.2 Projects participation

- INNOSTOCK 2012, The 12th International Conference on Energy Storage, 2012
- El almacenamiento de energía térmica como herramienta de mejora de la eficiencia energética en la industria (TES in industry), ENE2011-22722, 2012-2014.
- Mejora de la eficiencia energética en edificios mediante el almacenamiento de energía térmica, ENE2011-28269-C03-02, 2012-2014
- EUROTHERM Seminar Nº99 - Advances in thermal Energy Storage, 2014

Currently

- Identificación de barreras y oportunidades sostenibles en los materiales y aplicaciones del almacenamiento de energía térmica, ENE2015-64117-C5-1-R, Ministerio de Ciencia e Innovación, 2016-2018.
- Use of innovative thermal energy storage for marked energy savings and significant lowering of CO2 emissions (INNOSTORAGE), PIRSES-GA-2013-610692, 2013-2017.
- PhD on Innovation Pathways for TES (INPATH-TES), European Union's Horizon 2020 research and innovation programme under grant agreement No 657466, 2015-2018.

### 12.4.3 Organizing committee participation

- Innostock 12th International Conference on Thermal Energy Storage.
- Eurotherm Seminar nº 93 - Thermal energy storage and transportation: materials, systems and applications.
- INSPIRES July 19th, 2016: Behavioural and physical factors in the definition of energy building performance.