Green roof energy simulation

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May 2014

Abstract

Green roofs are key to provide living space, to adapt cities to the more extreme climatic conditions and to reduce energy use and CO_2 emissions. This study explores the impact of green roofs on building energy performance using the building energy simulation program EnergyPlus. An integrated green roof simulation module, developed by Sailor (2008), was used, which allows the energy modeller to explore green roof design options including growing media depth and vegetation characteristics such as plant type, height and leaf area index. The model has been tested successfully using observations from three monitored green roofs in Lisbon. A model sensitivity analysis was conducted on an adiabatic compartment, except the roof, and the findings showed that a combination of thicker soil, higher plant height and higher value of leaf area index (LAI) is the best solution to improve the building energy performance. Also, it was found that irrigation levels are very important in reducing cooling energy demand. Other simulations were conducted for both black and white roofs and three variations of green roofs (extensive, semi-intensive and intensive) for the three case studies located in Lisbon, and with different levels of roof insulation. The results reveal that semi-intensive and intensive green roofs can provide a reduction on energy consumptions when compared to black and white roofs, mostly for lower levels of roof insulation, and extensive green roofs are only a benefit for a non-insulated black roof, suggesting a solution for old buildings.

Keywords: Green roofs, Building energy simulation, EnergyPlus, Energy consumptions reduction

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1. Introduction

Since the Industrial Revolution, the burning of fossil fuels and human activities has been increasing the concentration of greenhouse gases (GHG) on the atmosphere, such as carbon dioxide (CO2), methane and nitrous oxide. The greenhouse gases controls the amount of radiation that is reflected to the earth surface, which being increased results in an elevation of the average surface temperature above what it would be in the absence of this gases. Due to the global warming, changes in the global water cycle, in reduction of the amount of snow and ice, in global mean sea level rise and in some climate extremes has been detected (IPCC, 2013).

In this context, there has been an increased awareness of global environment impacts on energy consumption. To address these concerns, in 2008 the European Parliament approved the "20-20-20" targets that set three key objectives for 2020: i) a 20% reduction in EU greenhouse gas emissions from 1990 levels; ii) raising the share of EU energy consumption produced from renewable resources to 20%; iii) a 20% improvement in the EU's energy efficiency. Within the European targets for 2020, there are two different approaches to be considered: i) sustainability of energy sources; ii) energy consumption efficiency. The present work focus on the last approach, more specifically on the energy efficiency of buildings. A significant part of the success of that goal will rely on making effective decisions about building characteristics, including roof type. It is estimated that buildings consumes about 40% of the total energy consumption which 37% is due to HVAC (Heating, Ventilation and Air Conditioning). With this in mind, it is important to evaluate the efficiency of this system.

There is relatively little quantitative information and a growing debate regarding the relative building HVAC energy savings of green roofs, and in Portugal, the information is still limited to a few studies focused on the discussion of some benefits of green roofs but none concerning a quantification

Nomenclature:

F_f	net heat flux to foliage layer (W/m2)
σ_f	fractional vegetation coverage
I_s	total incoming short-wave radiation (W/m^2)
α_f	albedo (short-wave reflectivity) of the canopy
ε_f	emissivity of canopy
I_{ir}	total incoming long-wave radiation (W/m^2)
T_f	foliage temperature (ºC)
ε_g	emissivity of the ground surface
σ	Stefan-Boltzmann constant (5.67x10^{-8} W/m^2 K^4)
T_g	ground surface temperature (ºC)
H_f	foliage sensible heat flux (W/m^2)
LAI	leaf area index (m^2/m^2)
ρ_{af}	density of air at foliage temperature (kg/m^3)
$C_{p,a}$	specific heat of air at constant pressure (1005.6 J/kgºC)
C_f	bulk heat transfer coefficient
W_{af}	wind speed with in the canopy (m/s)
T_{af}	air temperature with in the canopy (ºC)
L_f	foliage latent heat flux (W/m^2)
l_f	latent heat of vaporization at ground temperature (J/kg)
r''	surface wetness factor
q_{af}	mixing ratio for air within foliage canopy
$q_{f,sat}$	saturation mixing ratio at foliage temperature
H_g	ground sensible heat flux (W/m^2)
ρ_{ag}	density of air at ground surface temperature (kg/m^3)
L_g	ground latent heat flux (W/m^2)
C_h^g	sensible heat flux bulk transfer coefficient at ground layer
l_g	latent heat of vaporization at ground temperature (J/kg)
q_g	mixing ratio at ground temperature

of the energy savings. Consequently, a detailed energy consumption analysis of the effect of green roofs is needed to evaluate the impact of this constructive solution on buildings energy use.

This study aims to characterize the energy consumption of the HVAC in three buildings in Lisbon (Portugal), which have green roofs installed, compared to conventional roofs with a high albedo (white roofs) and a low albedo (dark roofs), using the simulation program EnergyPlus. An investigation of the building energy impact of green roof design decisions is also addressed, varying the soil and plant characteristics.

2. Green roofs

A green roof, also known as living roof, ecoroof or vegetated roof is a roof covered with vegetation and a growing medium. Beneath the growing medium and above the structural support the constructive system may be composed by a waterproofing membrane, root barrier, drainage and isolation, mostly depending on the antiquity of the building.

There are four types of green roofs: extensive, intensive, semi-intensive and brown roofs. The extensive roof is characterized by a thin growing medium (6-25cm), small plants, light and minimal maintenance. On the other hand, the intensive roof is characterized to require more maintenance, support a wider variety of plants, and to be heavier and thicker (15-70cm) than the extensive roof. The semi-intensive roof has the intermediate characteristics of the intensive and extensive roofs, and the brown roof is a new concept that consists in a roof with a growing medium but without vegetation to encourage biodiversity to develop on the roof.

The use of the green roofs has benefits and disadvantages. The main disadvantage is the initial cost of installing a green roof that can be between two and ten times more than a conventional roof, depending on the green roof type. The other main disadvantage is the additional mass of the soil substrate, retained water and vegetation that can be a concern to the structural resistance of the building. This makes it unlikely for intensive green roofs to be installed in older buildings and only in prepared ones. In older ones, the extensive roofs could be an option due to the lightweight. The benefits of green roofs include: i) reduce the urban heat island effect – remove heat from the air through evapotranspiration reducing temperatures of the surrounding air, and in a large scale could absorb about 80% of the emitted heat by human activities; ii) reduce stormwater runoff and prevent floods – retain rainwater in the substrate and then return it to the atmosphere trough transpiration and evaporation; iii) filter pollutants and heavy metals out of rainwater; iv) reduce air pollution and greenhouse gas emissions – vegetation has the power to filter the air; v) increase sound isolation – the soil helps to block lower frequencies and the plants block higher frequencies; vi) improve quality of life – green roofs can provide aesthetic value and habitat for many species, that otherwise have limited natural space in cities; vii) reduce energy use – absorb heat and act as a thermal insulator, reducing cooling and heating energy. In the present work, it is only concerned with the last referred benefit, the building energy performance of green roofs.

2.1 Green roofs energy simulations

Experimental measurements of how a green roof impacts rooftop surface temperatures and heat fluxes have been conducted by several studies (Lazzarin, Castellotti and Busato, 2005; Theodosiou, 2003) that found a reduction of the heat flux on the green roof compared to a conventional one. However, this reduction cannot be translated into direct knowledge of the impact of a green roof on the energy use in a building. This happens because the HVAC load doesn´t depend only on the quality of the roof but is also significantly dependent on internal and environment loads through windows and walls. One early study that did incorporate a comprehensive building model that explored the impact of a green roof on HVAC energy consumption was Niachou et al. (2001) and Wong et al. (2003) using the building energy software TRNSYS (TRaNsient SYstem Simulatin) and DOE-2, respectively. In their study, they represented the green roof simply by an increase on the roof thermal resistance and did not take into account the seasonally and diurnally varying shading and evapotranspiration effects of the growing medium and vegetation. The results from Niachou et al. (2001), compared to a conventional roof in an hotel located at Athens (Greece), indicates a 8% and 0% savings for the well-insulated roof and, 46% and 45% savings for the uninsulated roof on the heating season and cooling season, respectively. For the annual HVAC energy consumption indicated less than 2% savings for the well-insulated roof and 44% savings for the uninsulated roof. The Wong et al. (2003) studied a shopping center located in Singapore that indicated an energy annual savings of green roofs (compared to a conventional roof) of 10% for the well-insulated roof and 1% savings for the uninsulated. Therefore, it is important to note that the potential energy savings for green roofs is a strong function of actual insulation levels and climate conditions. Saiz et al. (2006) studied a residential building of eight stories in Madrid (Spain) with the software ESP-r (Environmental Systems Performance – research) where the green roof was represented by an increase on the roof thermal resistance and albedo trying to represent the evapotranspiration and shading that the vegetated roof provides. Their study indicates a 1,2% annual HVAC energy savings and that it influences only the three highest stories.

More sophisticated studies were conducted by Jaffal, Ouldboukhitine and Belarbi (2012) and Kotsiris et al. (2012) using the building energy software TRNSYS and models that represent the transpiration and shading provided by the vegetation and the evaporation of water from the growing medium. Jaffal, Ouldboukhitine and Belarbi (2012) study a detached house located in La Rochelle (France), indicating a 46% and 100% savings for the uninsulated roof and, a 0% and 86% savings for the well-insulated roof, on the heating season and cooling season, respectively. The high-energy savings of 100% for the cooling season is explained by the cold climate and low cooling energy dispended throughout the year. The same conclusion of the reduction of the HVAC energy savings with the insulation levels increase is also applied. In addition, the HVAC energy consumption of green roof increased (savings were reduced from 100% to 86%) with the insulation level on the cooling season explained by the reduction of heat absorbed by the growing medium and plants through evapotranspiration which is consistent with the studies of Lazzarin, Castellotti and Busato, 2005 and Theodosiou, 2003. Kotsiris et al. (2012) also studied a detached house but in Pikermi (Greece) with three different green roofs: i) high thermal resistance substrate and low vegetation; ii) low thermal resistance substrate and low vegetation; iii) medium substrate thermal resistance and high plants. The conclusion on the heating season is that higher thermal resistance of the growing medium is the key to maximize energy savings, while on the cooling season the type of vegetation is the one that influence more the energy savings. Their study indicates that HVAC energy savings on the cooling season was higher to higher plants and medium soil thermal resistance (15%) instead of high thermal resistance and lower plants (12%), which indicates the importance of evapotranspiration on the cooling season, working as a passive cooling system.

Sailor (2008) developed a physically based model of the energy balance of green roofs in a module incorporated in the software EnergyPlus. This author simulated a two story office building with the green roof model and compared with results from the soil surface temperature obtained experimentally, achieving an average bias (MBE) of 2,9ºC. Sailor (2008) explained that there are many degrees of freedom (such as height of plants, stomatal resistance and LAI) that if optimized would allow a lower bias, although it is inappropriate for validation purposes. Later, Moody and Sailor (2013) compared the simulation results with experimental data where they achieve a bias (MBE) of 1ºC. Sailor (2008) studied the office building in two different locations: Chicago that is characterised by warm humid summers and cold winters and on the other hand, Houston by hot humid summers and mild winters. The results on the cooling season indicates an HVAC energy savings of 9% to Chicago and 11% on Houston. Since the energy consumption on the heating system is 429 GJ for Chicago and 86 GJ for Houston, leading to an energy saving of 39 GJ and 9 GJ, respectively, it is possible to conclude that the energy savings written in percentage has to be carefully used. On the cooling season, the energy savings was similar, 2% for both cities. Ascione et al. (2013) used the same green roof model in EnergyPlus to study an office building in Tenerife (Spain) and Oslo (Norway) varying the factor LAI (Leaf Area Index), which represents the projected area of all leaves divided by the roof surface area. In Tenerife, which has a hot climate throughout the year, the annual energy use for the heating season is almost zero. On the other hand, on the cooling season the energy consumption for cooling is substantial. The HVAC energy savings on the cooling season varies from 1% to 11%, with LAI = 0,8 and LAI = 5,0, respectively, suggesting the importance of evapotranspiration on cooling energy use. In Oslo the same conclusion is achieved, despite of the cooling energy consumption is lower than in Tenerife. The energy savings on the cooling season reaches -1% when LAI = 0,8, which is explained by the lower effect of evapotranspiration and protection of the roof. On the heating season, Oslo indicates a 5% heating energy savings for LAI = 5,0 and 6% heating energy savings for LAI = 0,8 because of the extra protection from the solar radiation that vegetation provides.

In conclusion, each building with its own characteristics and different locations lead to different performances of HVAC energy consumptions of buildings with green roofs. Based on the previous studies, in the cooling season, higher plants and higher LAI are the most essential characteristics and in the heating season, lower plants, lower LAI and high thermal insulation are the key to maximize the green roofs thermal performance. So it is necessary to balance those parameters to achieve an optimized design.

3. EnergyPlus

EnergyPlus was selected as the simulation platform for the analysis of the impact of green roofs on thermal performance of buildings since it is one of the most advanced building energy simulation programs and has incorporated a green roof model. EnergyPlus is an energy analysis and thermal load simulation program that has its roots in two other simulation programs, both written in Fortran: BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2, that born out of concerns driven by the energy crisis of the early 1970s in United States of America. Both programs had some strengths and technical limitations such as the inability to account properly for feedback of HVAC calculations into the overall energy balance analysis, which led to inaccurate space temperatures estimates. Therefore, the developers of EnergyPlus sought to combine the best features from each code in a modular framework that facilitates ongoing development and incorporation of new features from the user community, which the green roof model is an example. EnergyPlus models heating, cooling, lightning, ventilation and other energy flows based on indoor and outdoor environmental conditions. To conduct a simulation two input files are required, namely a building input data file (IDF), which has all the characteristics of the study case, and a weather data file, which has the information of the location climate. The main limitation of EnergyPlus is the difficulty to define the geometry of the building, which has to be done by a coordinate system. As it is a difficult process, the OpenStudio Plug-in allows users to quickly generate geometry for EnergyPlus with the program Google SketchUp that is a very intuitive drawing tool.

3.1 Green roof model

Due to the modular structure of EnergyPlus, it was implemented a green roof model by Sailor (2008) which is used in the present study. This model functions as an integral component of the simulation software performing an energy balance on a vegetated rooftop and was based on the fast all season soil strength model (FASST) developed by Frankenstein and Koening (2004) for the US Army Corps of Engineers. In particularly, this model takes into account the long and short wavelengths radiation exchanges by the soil and vegetation, effects of vegetation on convective (sensible heat) thermal flow, evapotranspiration (latent heat) through soil and vegetation and heat storage and transfer through the substrate (Figure 1). The model has also the capability to change thermal properties of the growing medium with soil moisture level. Although, the only algorithm available in EnergyPlus that works with the ecoroof model (CTF) is not prepared to vary the thermal properties, so it is not taken into account. Future refinements of the model and EnergyPlus iteration expect to consider the thermal properties changes.

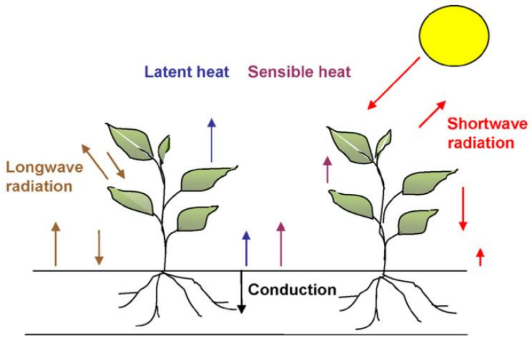

Figure 1 - Simplified representation of the energy balance in a green roof (Sailor, 2008)

The green roof model of Sailor (2008), is a one-dimensional model that contains energy budgets for both the foliage layer and the ground surface. The main heat fluxes that describe the heat balance of the vegetation are the following:

- The short and long wave radiation absorption and long wave radiation emitted by the foliage ($\sigma_f[\,I_s(1-\alpha_f)+\varepsilon_f I_{ir}-\varepsilon_f\sigma T_f^4]$)
- The long wave radiation exchange between the foliage and the soil surface ($\frac{\sigma_f\varepsilon_f\varepsilon_g\sigma}{\varepsilon_1}(T_g^4-T_f^4)$)
- The convection (sensible) heat exchange between the foliage and the air in the canopy ($H_f=(1{,}1\times LAI\rho_{af}C_{p,a}C_f W_{af})\times(T_{af}-T_f)$)
- The latent heat flux by evapotranspiration in the foliage ($L_f=l_f\times LAI\rho_{af}C_f W_{af}r''\times(q_{af}-q_{f,sat})$)

Hence, the foliage energy balance is given by Equation (1).

$$F_f=\sigma_f[\,I_s(1-\alpha_f)+\varepsilon_f I_{ir}-\varepsilon_f\sigma T_f^4] + \frac{\sigma_f\varepsilon_f\varepsilon_g\sigma}{\varepsilon_1}(T_g^4-T_f^4)+H_f+L_f \quad (1)$$

The main heat fluxes that describe the heat balance of the soil surface level are the following:

- The short and long wave radiation absorption and long wave radiation emitted by the soil ($(1-\sigma_f)[I_s(1-a_g)+\varepsilon_g I_{ir}-\varepsilon_g T_g^4]$)
- The long wave radiation exchange between the foliage and the soil surface ($\frac{\sigma_f\varepsilon_g\varepsilon_f\sigma}{\varepsilon_1}(T_g^4-T_f^4)$)
- The convection (sensible) heat exchange between the soil and the air in the canopy ($H_g=\rho_{ag}C_{p,a}C_h^s W_{af}\times(T_{ag}-T_g)$)
- The latent heat flux by evapotranspiration in the soil ($(L_g=C_h^g l_g W_{af}\rho_{ag}\times(q_{af}-q_g)$)
- The heat flux conducted through the soil ($K\times\frac{\partial T_g}{\partial z}$)

Hence, the soil energy balance is given by Equation (2).

$$F_g=(1-\sigma_f)[I_s(1-a_g)+\varepsilon_g I_{ir}-\varepsilon_g T_g^4] - \frac{\sigma_f\varepsilon_g\varepsilon_f\sigma}{\varepsilon_1}(T_g^4-T_f^4)+H_g+L_g+K\times\frac{\partial T_g}{\partial z} \quad (2)$$

An important aspect to be noted is the influence of the fraction of vegetation coverage (σ_f) which impacts significantly the heat fluxes in the soil and foliage, that represents the shadow that vegetation provides. This fraction of vegetation coverage is not an input but an estimative dependent only on the factor LAI (Leaf Area Index) - Equation (3). LAI is essentially the projected area of all leaves divided by the soil surface area.

$$\sigma_f=1-\exp(-0{,}75\;x\;LAI) \quad (3)$$

The model also allows the user to specify various aspects of the green roof construction including height of plants, leaf emissivity and reflectivity, minimum stomatal resistance and thickness, density, thermal conductivity, specific heat and thermal, visible and solar absorptance of the soil. A detailed description of the green roof model is not the focus of this study, therefore it is suggested the Sailor (2008) and Frankenstein and Koening (2004) work for the interested reader.

4. Study cases and model evaluation

The investigated cases concerned on two compartments in *Fundação Calouste Gulbenkian* and one compartment in *ETAR de Alcântara,* both located in Lisbon (Portugal) and with green roofs in their constitution. The characteristics of all the compartments are a representation of the existing ones and in accordance to the Portuguese regulations.

4.1.1 Study case 1 – Gulbenkian: Technical sound room

The first study case in *Gulbenkian* is a technical sound room fully adiabatic, except the roof addressed, and with a total floor area of 17 m^2. The modelled created in Google SketchUp is presented in Figure 2.

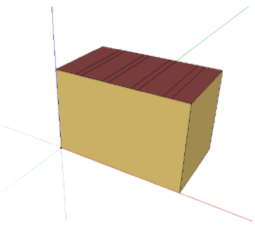

Figure 2 - Technical sound room model

The modelled green roof is a representation of the grass lawn (figure of Table 1) existing on the rooftop, above a 0,2 m concrete slab and 0,1 m gravel, without any additional insulation. The main characteristics of the green roof baseline is presented in Table 1.

Table 1 - Green roof 1 baseline main characteristics

Height of plants (m)	0,10	
LAI	2,0	
Soil thickness (m)	0,25	
Irrigation (mm/day) (Jun. to Sep.)	6	

4.1.2 Study case 2 – Gulbenkian: Rehearsal room

The second study case, also in *Gulbenkian,* is a rehearsal room fully adiabatic, except the roof addressed and a glazed facade, with a total floor area of 185 m^2. The rooftop characteristics are the same presented in Table 1, as Figure 3 proves, including concrete slab and gravel thickness, roof insulation and green roof characteristics.

Figure 3 - Rehearsal room green roof

The modelled created in Google SketchUp is presented in Figure 4.

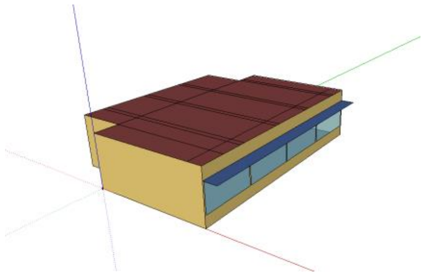

Figure 4 - Technical sound room model

4.1.3 Study case 3 – ETAR: Conference room

The last study case is located in *ETAR de Alcântra*, and concerned a conference room fully adiabatic, except the roof addressed and a glazed facade, with a total floor area of 93 m^2. The modelled created in Google SketchUp is presented in Figure 5.

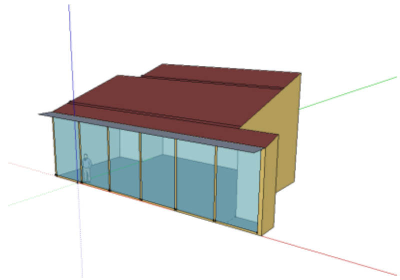

Figure 5 - Technical sound room model

The modelled green roof is a representation of the plants (figure of Table 2) existing on the rooftop, above a 0,2 m concrete slab and a varying thickness of lightweight gravel (0,4 to 0 m), without any additional insulation. The main characteristics of the green roof baseline is presented in Table 2.

Table 2 - Green roof 2 baseline main characteristics

Height of plants (m)	0,4	
LAI	4,0	
Soil thickness (m)	0,65	
Irrigation (mm/day) (Jan. to Dec.)	6	

4.2 Model evaluation

The three green roofs were thoroughly monitored by Valadas (2014) providing useful data for validation. Specifically, multiple temperature and heat fluxes sensors were installed to measure soil and roof surface temperatures and roof heat flux. In addition, local weather conditions, such as outdoor air drybulb temperature and solar radiation were measured and implemented in the model evaluation in EnergyPlus. Also, it was created a precipitation and green roof irrigation schedule for more accurate results.

While it was measured and compared a wide range of experimental data with simulation results, in this paper it will only address the analysis of soil temperature since it evaluates the green roof model used and exists a background studies to compare results (Sailor (2008) and Ouldboukhitine, Belarbi and Sailor (2014)). Those authors used a quantitative comparison in terms of mean bias error (MBE) and root-mean-square error (RMSE) for error analysis of the simulation results (Equation (4) and Equation(5)), which was also conducted in the study cases.

$$MBE = \frac{\sum_{i=1}^{n}(X_{sim,i} - X_{\exp,i})}{n} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{sim,i} - X_{\exp,i})^2}{n}} \quad (5)$$

For the measured periods in the Gulbenkain rehearsal room and in the ETAR conference room, Figure 6 and Figure 7 show both simulation and experimental results, for heating and cooling season. In the technical sound room, in Gulbenkian, It hasn´t been conducted soil temperatures measures due to equipment difficulties. MBE and RMSE values for the two study cases and for Sailor (2008) and Ouldboukhitine, Belarbi and Sailor (2014) studies are shown in Table 3.

The calculate values for soil surface temperature indicate that MBE values are lower than the ones calculated by Sailor (2008) and Ouldboukhitine, Belarbi and Sailor (2014), and the RMSE values are similar in every studies. Also, it is possible to conclude that exists an agreement between simulation and experimental results and that the model has the ability to track diurnal and seasonal variations. From this validation work, it is found that the computer simulation program EnergyPlus with green roof model, incorporated by Sailor (2008), performs adequately and is reliable for predicting the thermal performance of green roof system in the present study.

Table 3 - MBE and RMSE of case studies soil surface temperatures compared to other authors

	Ouldboukhitine, Belarbi e Sailor (2014)		Sailor (2008)		Rehearsal room		Conference room	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Soil surface temperature (ºC)	1	-	2,9	4,1	0,66	3,49	0,51	4,1

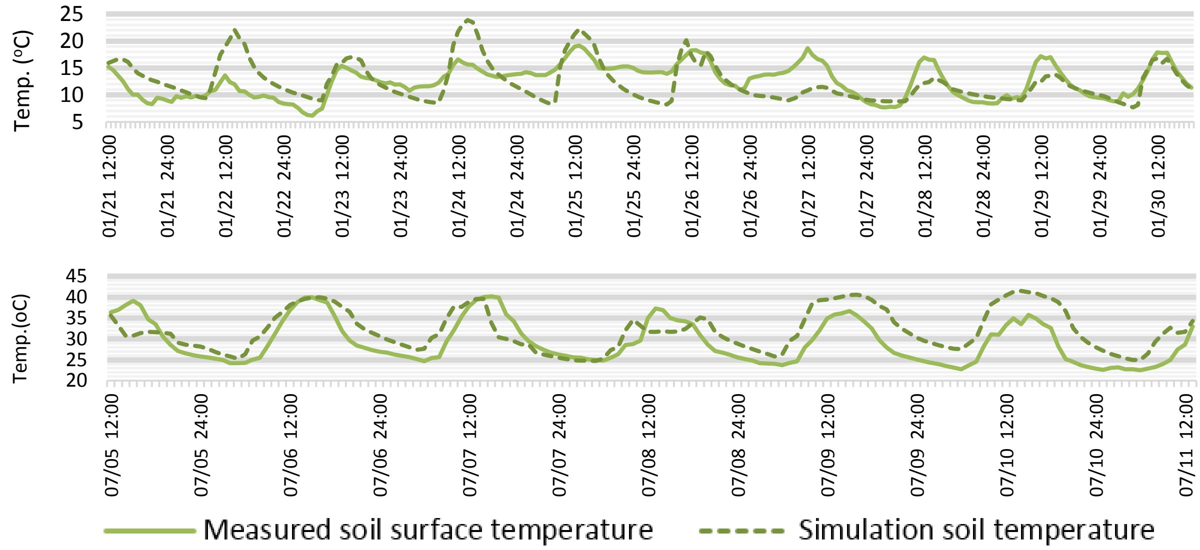

Figure 6 – Simulation results compared to measured soil surface temperatures for the green roof at the rehearsal room

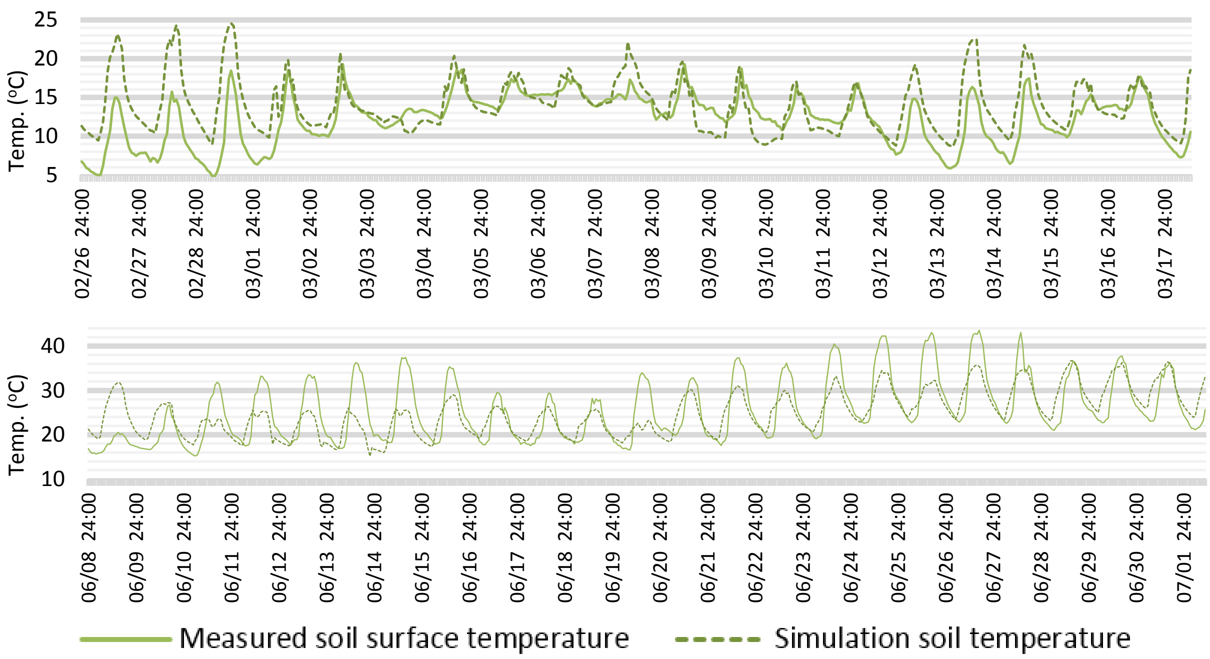

Figure 7 - Simulation results compared to measured soil surface temperatures for the green roof at the conference room

5. Model sensitivity analysis

Having conducted an evaluation of the model performance using the green roof model, this chapter explores the model sensitivity to key parameters, in heating and cooling energy consumption for the set point temperatures 20 and 25ºC, respectively. In the present study, the impact of soil thickness, LAI, plant height and irrigation will be analysed. For this purpose, it was selected the case study 1 – Gulbenkian: technical sound room due to the compartments fully adiabatic characteristics, except the roof.

It is important to notice the compartment location. Lisbon (Portugal) has a Mediterranean climate (Koppen climate classification: Csa) with four defined seasons, with mild winters and warm summers. In general, the summer presents temperatures between 16 and 35ºC, autumn between 12 and 27 ºC, winter between 4 and 17 ºC and spring between 8 and 26 ºC. Precipitation has an average of 600 mm per year and mostly between October and April.

Figure 8 shows the energy consumption of 4 cases of green roofs for both heating and cooling season to the technical sound room. As these parameters vary, so too does the energy performance of the green roof. Irrigation is a key to maximize the green roof performance in the cooling season and to increase energy consumption in the heating season. It was conducted simulations with no irrigation and with 6 mm/day activated everyday of the year, and it was possible to conclude that heating energy consumption is lower for no irrigation and cooling energy consumption is lower when irrigation is activated (considered 6 mm/day, indicated by Cudell (2000)). This is because irrigation increases the cooling effect from the transpiration of plants and water evaporation from the soil. Hence, an optimized solution is shown in Figure 8 where irrigation was only considered in the cooling season.

Increasing the LAI increases the shading on the roof, thereby reducing the solar heat gain, and the transpiration of plants resulting in a cooling effect. It then follows that increasing the LAI, decreases the cooling energy consumption and increases the heating energy consumption. In general, increasing the LAI results in a decrease in the total energy consumption since the decrease of the cooling energy is higher than the increase of the heating energy consumption. It was also investigated energy consumption with different plant heights. Increasing the plant height results in an increase of the wind velocity within the canopy, decreasing the aerodynamic resistance, and facilitating the transpiration cooling effect. As so, higher plants lead to higher energy consumption in the heating season and lower energy consumption in the cooling season, as Figure 8 proves.

Increasing the soil depth of the green roof, increases insulation and thermal mass. As so, it decreases the energy consumption in general, except for the cooling season with high LAI values, as shown in Figure 8. This is due to the extra insulation of deeper soil that doesn´t allow the roof to take full advantage of evapotranspiration cooling effect. However, increasing the soil depth results in lower total energy consumption in all cases.

Nowadays, a solution for older buildings concerns in extensive roofs due to the thinner soil depth because of extra structural loads. In addition, it is possible to use lighter substrates with lower density. Simulations were conducted to investigate this matter, varying the soil density for green roof characteristics: LAI = 0,1, plant height = 0,05 m and soil depth = 0,1 m. The results showed that decreasing soil density from 1500 to 300 kg/m², increased total energy consumption in 0,4 %. It is possible to conclude that this is not a significant variation, so an extensive green roof with lighter substrates can be an option for older buildings, without losing the benefits of green roofs.

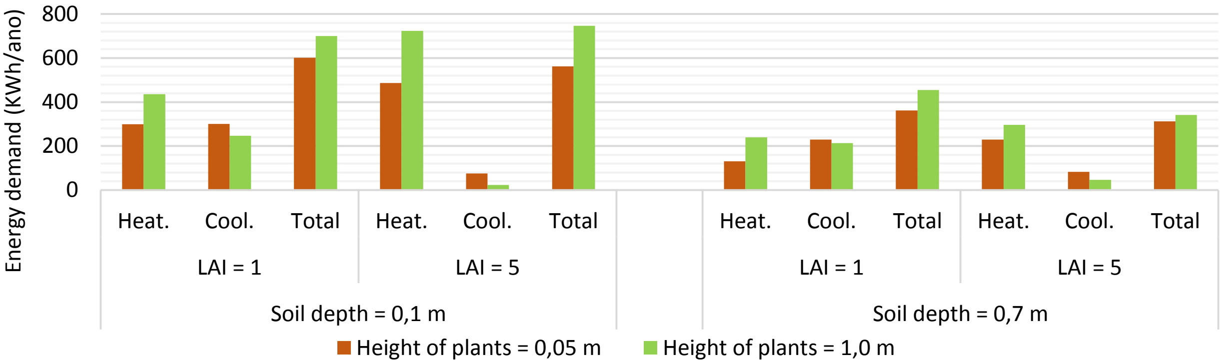

Figure 8 – Optimized energy consumption for key parameters variation with irrigation only for the cooling season of 6 mm/day

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6. Green roofs, white and black roof comparison

The purpose of this chapter is to compare the energy performance between green roofs and conventional ones, namely a highly reflective roof (commonly known as white roof or cool roof) and highly absorptance roof (black roof). Regarding the green roofs, it was consider three types of green roofs, which represents the three main typologies addressed in chapter 2. The main characteristics of these five roofs studied are presented in Table 4. The irrigation considered on the green roofs was the value indicated by Cudell (2000) of 6 mm/day and activated every day of the year and only when the soil moisture is below 40% (Sailor (2008)). This way, the irrigation will adapt the vegetation needs.

Simulations were carried out for the three case studies presented in chapter 4 and for different insulation levels to evaluate the energy performance on more insulated buildings. All the comparisons are made between the same insulation level. Table 5, Table 6 and Table 7 show the simulation results for both heating and cooling season, for the three case studies and for the five roof solutions.

Table 4 - Characteristics of the 5 roofs studied

Conv. roofs	Black	Membrane (5 mm)	Albedo = 0,2
	Withe	Membrane (5 mm)	Albedo = 0,8
Green roofs	Extensive	LAI	1,0
		Height of plants (m)	0,10
		Soil depth (m)	0,25
	Semi-intensive	LAI	2,5
		Height of plants (m)	0,50
		Soil depth (m)	0,35
	Intensive	LAI	5,0
		Height of plants (m)	1,0
		Soil depth (m)	0,70

Table 5 - Technical sound room energy consumptions for the five roof solutions (kWh/year/m²)

	Extensive green roof			Semi-intensive green roof			Intensive green roof			Black roof (Albedo=0,2)			White roof (Albedo=0,6)		
XPS (cm)	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total
0	17.5	55.2	72.7	19.4	19.7	39.1	17.3	9.4	26.7	33.5	59.6	93.1	60.5	13.3	73.7
2	8.7	42.9	51.6	11.9	17.7	29.6	11.6	10.0	21.6	18.0	34.1	52.1	30.3	10.8	41.0
4	5.6	34.7	40.3	8.4	16.2	24.6	8.5	10.5	19.1	12.0	27.6	39.6	19.8	10.9	30.7
8	3.1	27.3	30.4	4.8	15.4	20.2	5.2	11.1	16.3	6.6	22.2	28.9	11.3	11.3	22.6

Table 6 – Rehearsal room energy consumptions for the five roof solutions (kWh/year/m²)

	Extensive green roof			Semi-intensive green roof			Intensive green roof			Black roof (Albedo=0,2)			White roof (Albedo=0,6)		
XPS (cm)	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total
0	5.8	54.3	60.1	6.4	40.3	46.7	6.1	35.4	41.5	9.3	51.4	60.7	13.4	34.1	47.6
2	4.3	51.0	55.4	4.9	40.5	45.4	4.9	36.6	41.5	6.8	47.0	53.8	9.2	35.2	44.4
4	3.7	49.1	52.7	4.2	40.5	44.7	4.3	37.3	41.6	5.4	45.6	51.0	7.1	36.2	43.3
8	3.0	46.8	49.8	3.3	40.8	44.1	3.5	38.5	41.9	4.1	44.2	48.3	5.1	37.6	42.7

Table 7 – Conference room energy consumptions for the five roof solutions (kWh/year/m²)

	Extensive green roof			Semi-intensive green roof			Intensive green roof			Black roof (Albedo=0,2)			White roof (Albedo=0,6)		
XPS (cm)	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total
0	17.7	51.8	69.5	18.1	41.6	59.7	17.6	39.0	56.6	22.3	48.1	70.4	27.0	36.9	63.9
2	15.9	46.6	62.4	16.7	41.4	58.1	16.8	39.7	56.4	18.3	43.5	61.8	20.4	38.5	58.8
4	15.4	45.1	60.5	16.2	41.3	57.5	16.2	39.9	56.2	17.1	43.0	60.1	18.5	39.3	57.8
8	15.1	43.9	59.0	15.7	41.3	57.0	15.8	40.2	56.0	16.3	42.4	58.7	17.2	39.9	57.1

The results show that in every cases the heating energy consumption decreases with insulation level. On the other hand, in the cooling season, the energy consumption increases with insulation level for green roof with high LAI and plant height. This is because the extra insulation doesn´t allow the roof to take full advantage of evapotranspiration cooling effect, as concluded in chapter 5. In addition, with higher insulation levels, the heat losses are hampered. For an easier analysis, Figure 9 and Figure 10 show the energy savings of green roofs compared to the black and white roof.

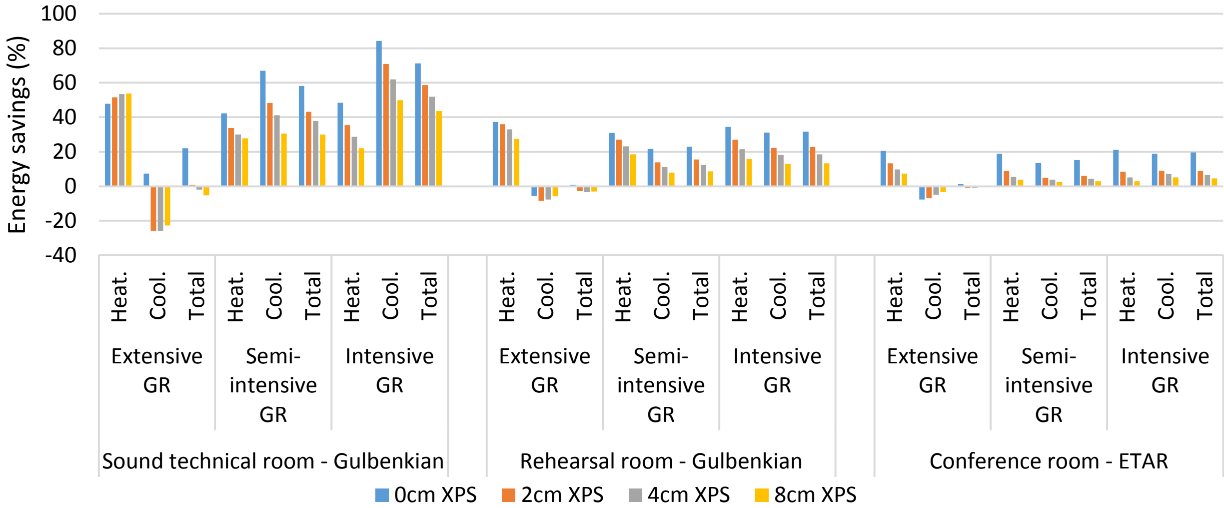

Figure 9 - Green roof energy savings compared to the black roof

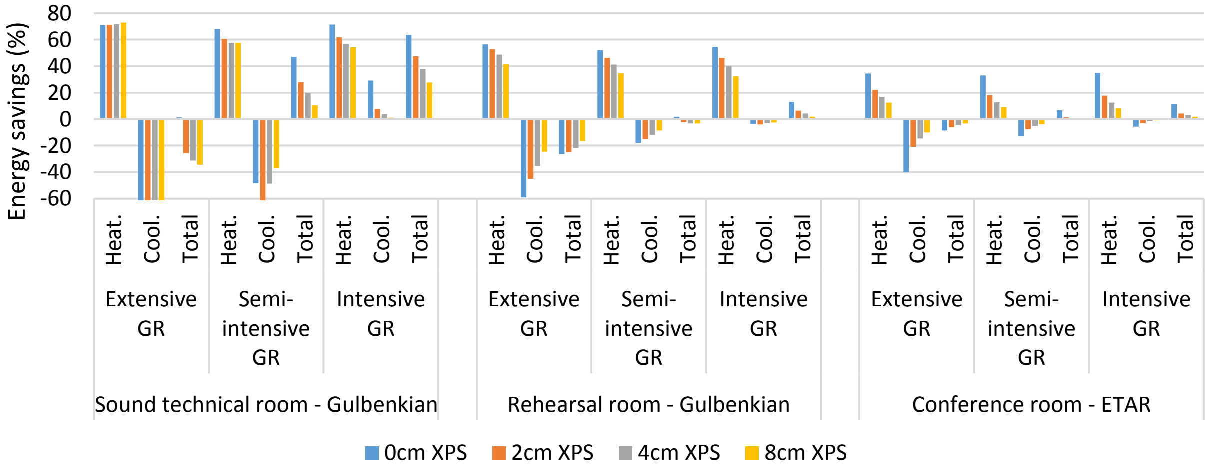

Figure 10 – Green roof energy savings compared to the white roof

The green roof is shown to reduce heating energy use for all buildings compared to the black and the white roof. On the cooling season, only the semi-intensive and intensive green roofs presents energy savings compared to the black roof due to the significant roof protection and evapotranspiration cooling effect. Regarding the white roof, none of the green roof solutions is an option to reduce cooling energy use in any buildings. This conclusion indicates that despite the cooling effects of green roofs, a highly reflective roof (white roof) is more effective on energy performance, as was concluded in chapter 2.

Concerning total energy consumption, semi-intensive and intensive green roofs are a solution to reduce energy use for low insulation levels compared to both black and white roofs. It is also possible to understand that energy savings concerned the technical sound room are higher because of its fully adiabatic characteristic, except the roof. For older buildings (lower insulation levels) with black roofs and structural limitations, extensive green roofs can be a solution to reduce energy use. It was found 22% of energy savings in technical sound room and 1% in the other case studies.

7. Conclusions

This work consisted in the analysis of green roof energy performance with the software EnergyPlus, which presents a green roof model. Green roofs are very difficult to be modelled and correctly imputed in calculation tools because of high number of variables. Although, It was understood that this model can consistently reproduced the diurnal and seasonal variation of the soil surface temperature. Also, the model sensitivity analysis revealed a physically realistic sensitivity to key parameters such as height of plants, LAI and soil depth. It was concluded that higher LAI and height of plants are the key to maximize energy savings on the cooling season, and higher soil depth is the solution to reduce energy consumptions on the heating season.

Comparisons were undertaken between conventional roofs and different green roof typologies leading to results showing that it can be a solution to reduce energy use mostly in uninsulated buildings. In addition, green roofs with high values of LAI and height of plants are the best solution for energy savings.

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