Green Roof Energy Simulation

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May 2018

Abstract

With the increasing concern about our planet´s health observed in the last years, green roofs arise as a more sustainable option to the reduction of energy consumption in the HVAC systems and consequently lower the greenhouse gas emissions. The main purpose of this study is to evaluate the influence of semi-intensive green roofs in the energy performance of buildings, using the simulation program EnergyPlus which contains a vegetated roof model. The study began with a calibration, using four trays (T3, T5, T6 and T7) present in ISA, Lisbon, containing distinct samples of green roofs. It has been confirmed that the model represents the thermal behavior of these roofs, but with different peak values. Then a sensitivity analysis was conducted. Results have shown, for the climate of Lisbon, that thicker soils and dense vegetation represent the best options for the reduction in energy consumption. Afterward all the four green roofs at ISA were compared with two common flat roofs in Portugal – white and black – in respect to energy performance. The level of insulation (XPS) was also evaluated. It was concluded that all four green roofs perform better than any of the other flats roofs in an annual analysis and the white roof is the one that performs better in summer, obtaining similar results when compared to the green roofs. Results also have shown that savings of green roofs in relation to the other flat roofs are substantially lowered when the level of insulation is high.

Keywords: green roofs, energy efficiency, EnergyPlus.

1 Introduction

In today's society, sustaining the environment is becoming an increasingly important issue. Consumers, businesses and institutions are making an effort to be environmentally conscious for the sake of the planet. In addition, businesses and institutions have the incentive of appearing more environmentally conscious to the public, and are beginning to forgo immediate economic gains for the sake of engaging in more environmentally sustainable activities [1]. Green roof technology is one possibility for reducing the environmental impact of a building [1].

The main purpose of this study is to analyze the energy consumption of the HVAC systems in buildings using green roofs. In order to achieve that, the energy simulation program EnergyPlus is used which is considered to represent the building, the HVAC systems and therefore its energy consumption. This program contains a specific Green Roof Model developed by [2] which allows to characterize accurately the components of a green roof. It is considered that this model represents with quality the behavior of vegetated roofs. Since in this work there was no real building available to conduct the experimental procedure associated with this simulation work, a set of four metallic trays located at Instituto Superior de Agronomia, Lisbon, were used. These trays contained samples of soils and vegetation that could correspond, in a larger scale, to real green roofs. The experimental data (temperatures and heat fluxes) obtained was then compared with the output information provided by the model developed in EnergyPlus. This process is called the calibration of the model. After calibration the model approximates the thermal performance of the green roof. Then a sensitivity analysis is conducted. This analysis consists on evaluating the relative importance of each of the parameters comprising green roofs and to observe its energy performance when a variation on the values of the parameters occur. Then the four roofs are compared with two conventional roofs common in Portugal – white roofs and black roofs – in terms of energy consumption for Lisbon climate. In the last chapter the main conclusions are shown and the suggestions for future developments in this subject are presented.

2 Green roofs

Green roof is a layered system comprising of a waterproofing membrane, growing medium and the vegetation layer itself. Green roofs often also include a root barrier layer, drainage layer and, where the climate necessitates, an irrigation system [3]. A green roof offers a building and its surrounding environment many benefits. These include stormwater management, improved water run-off quality, improved urban air quality, extension of roof life and a reduction of the urban heat island effect [3].

Nomenclature	
T3	Tray Number 3
T5	Tray Number 5
T6	Tray Number 6
T7	Tray Number 7
Wi	With insulation
Ti	Inside temperature
Tsi	Surface inside temperature
Tse	Surface outside temperature
Fsi	Heat flux on internal surface

Another important aspect is the economy. Authors [4] affirm savings can reach 80% in the cooling season and 50% in an annual analysis. The main disadvantages of this solution are related to superior complexity in the construction, the increased cost associated with construction and maintenance and a higher load transmitted to the structure. Previous studies [2, 5] state green roofs are very well suited for retrofitting old buildings.

2.1 Previous studies

Green roofs have been object of study especially in the last decades. The major part are directed to its environmental and sustainability component and also its technical aspects, from its construction to its maintenance. There are also many experimental studies related to thermal end energetic behavior and analysis. Specifically in the energy simulation of green roofs, several works have been developed in the last years. The main works regarding this issue are [2, 4, 6, 7, 8, 9] which have used EnergyPlus simulation program for different climates. Authors [10 – 14] have used the TRNSYS software in their simulations. Studies [15 – 17] employed other software in their energy simulations.

In the cooling season, energy savings can reach 80% when comparing a green roof with a conventional roof. This value was obtained by [4] in a single floor residential building. Authors [8] achieved a total saving of 18% in a multi floor building without thermal insulation. Authors [13, 18] refer in their studies the importance of the evapotranspiration process in the reduction of energy consumption in the cooling season. Previous works [10, 19] state that the impact of green roofs in energy savings is heavily reduced with the introduction of thermal insulation. Some authors [6] analyzed the importance of the vegetation characteristics and concluded that higher and denser plants lead to the greater savings, which can reach 11%. In work [2] the author varied the LAI parameter and determined that higher values of this parameter lead to major savings. Other studies [16] obtained the same conclusions.

In the heating season, the energy savings can reach 48%. This value was achieved by [10] for an uninsulated roof. Several authors [4, 7, 8, 13, 14] affirm the increase on energy savings is directly related to the reduction in insulation. Thereby these authors highlight the importance of the application of green roofs in buildings with low level or absence of insulation. Some authors [13] concluded that greater savings are achieved when the thermal conductivity of the soil is lower. Sailor [2] determined that thicker soils lead to superior savings and the increase in LAI is harmful in terms of energy savings in this season.

The location or climate is also very important. Sailor [2] investigated the energy savings for two cities with very different climates, Houston and Chicago. Chicago has an extreme winter, therefore the highest energy consumption in an annual analysis (429 GJ) but it is Houston (86 GJ) who has the greater energy savings. Study [6] analyzed the performance of green roofs for six different cities in Europe. In the heating season, the greater savings are achieved in colder climates. In the cooling season the authors found similarity in the percentage values of savings, which represents a very large saving in absolute terms in hot climates, to which correspond greater energy consumption in this season. Authors [7] studied the energy savings for 3 Mediterranean cities with different climates. Barcelona is the city with lower temperatures and higher values of precipitation and Cairo is the example of higher temperatures and reduced values of precipitation. Palermo represents the intermediate climate between the other two. In the cooling season the city who presented the greater savings was the coldest (Barcelona) since the consumption is almost negligible in this season. In the heating season the larger savings were obtained in Palermo. In a one year analysis the city that presented the bigger savings was Barcelona, a fact which indicates green roofs perform better in cold climates. Some authors [9] investigated the energy savings in two Italian cities with different climates, Milan and Catania. The study was based in an office building with moderate level of insulation, where the superior savings were obtained in the hotter and drier city (Catania).

Other kind of studies were conducted, namely the comparison between green roofs and cool roofs, the ones represented by high values of albedo. This study [7] concluded cool roofs allow savings about 40% in hotter climates due to its high reflectance properties, in particular Cairo. In the heating season it has an adverse effect by not being able to take advantage of the solar radiation and consequently increase energy consumption. Some studies [6] conducted an economical study on green roofs. They included in their analysis the savings in energy consumption with the introduction of green roofs and the costs with the irrigation system and initial investment. They concluded that only in Oslo (colder climate) could exist economic advantages in this kind of investment but the payback time would be about 143 years. They also state this option will never be profitable in the hotter climates in the southern Europe if only energy saving is considered. The authors also studied the possibility of economic incentives by the respective governments. If these would assume half of the costs, the payback time could be reduced for about 5-10 years in the cities with hotter and drier climates.

3 EnergyPlus

The program chosen for the simulations was EnergyPlus. It is a building energy simulation program used all over the world. This program was chosen because it includes a specific model to analyze green roofs introduced by Sailor [2]. EnergyPlus is a simulation engine so it does not possess a graphical interface. To overcome this obstacle SketchUp Make was used which allows the creation of the compartment/building geometry in a very expeditious way. So that the drawing can be associated to EnergyPlus it is necessary to use the Plug-in OpenStudio which inserts directly in EnergyPlus the fields related to the geometry of the compartment/building since it allows saving the file as IDF format.

4 Case Study and model calibration

The case study is a set of four experimental trays containing samples of soil and vegetation, all with different combinations, which any of them could correspond to a semi-intensive green roof in a larger scale. The trays are located in the roof of the building Herbário João Vasconcellos, in ISA, Lisbon. The trays are rectangular, whose base is more profound than the laterals to accommodate the samples of soil. They are supported in a metal frame which elevates them about 80 cm from the rooftop floor. The analyzed trays were wrapped with XPS plates 10 mm thick on all sides except the top, in order to isolate the inferior part of the tray from the outside conditions and ensure that the heat exchanges occur only by the green roof (sample). In order to evaluate the influence of insulation in the energy performance of green roofs, a thinner plate of XPS (3 cm) was placed in an internal zone of the tray. With this procedure, two zones were created: non-insulated and with insulation (WI zone).

4.1 EnergyPlus Model

The model created with SketchUp in order to characterize the experimental trays is represented in Figure 2. The materials that compose the trays and their characteristics are presented in Table 1.

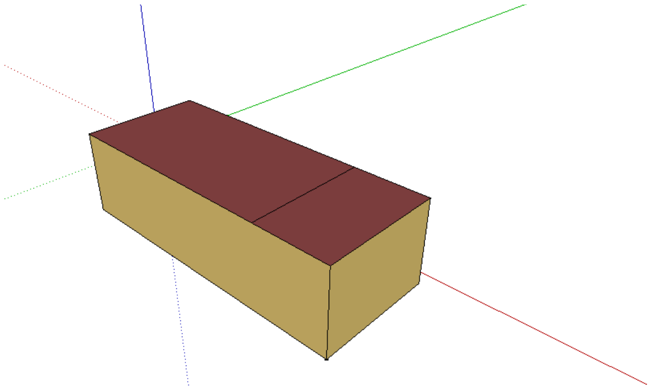

Figure 1 – Geometric model of the tray in SketchUp

The model is composed by a container with a parallelepiped shape with base dimensions 2,5m x 1,0m and 70cm high. It is composed by a floor, four walls with the same thermal properties and a roof divided in two parts: insulated and non-insulated. The draining system is composed by a filter, a drainage layer and a mechanical protection layer, from the inside to the outside.

Table 1 – Characteristics of the materials comprising the experimental trays

Materials	XPS
Roughness	Medium Smooth
Conductivity (W/(m.ºC))	0,037
Density (kg/m^3)	33
Specific Heat (J/(kg.ºC))	1200
Thermal Absorptance	0,9
Solar Absorptance	0,5
Visible Absorptance	0,5

4.2 Green roof trays

In order to accomplish this work three sets of data were used: the summer campaign conducted by Meneses [20] and the winter and summer campaigns conducted by Neves [21].

Table 2 – Green roofs baseline main characteristics

	Tray	T3	T5	T6	T7
Plant	Height of Plants (m)	0,25	0,45	0,50	0,25
	LAI (Leaf Area Index)	2,5	1,6	1,3	2,3
	Leaf reflectivity	0,24	0,18	0,18	0,29
Soil	Thickness (m)	0,13	0,13	0,13	0,13
	Conductivity of dry soil (W/m.°C)	0,4	0,3	0,3	0,3
	Density of dry soil (kg/m^3)	883	383	383	383
	Specific heat of dry soil (J/kg.°C)	1200	1000	1000	1000
	Solar Absorptance	0,6	0,6	0,6	0,6
	Visible Absorptance	0,6	0,6	0,6	0,6

The characteristics assumed for the four experimental trays are presented in Table 2. Height of plants was measured in situ, LAI parameter was determined from data gathered in experimental campaigns and based on studies [2, 5] and the leaf reflectivity was obtained in the experimental study [20]. The remaining parameters were adopted the pre-defined in the program. Concerning the soil, thickness was measured in place and density was consulted in the experimental study [20]. The conductivity and specific heat of dry soil were obtained in the work [22] based on soil composition. The other parameters were adopted the standard in the program.

4.3 Model Calibration

In the winter campaign, a lamp associated to a thermostat was used to maintain the temperature in comfort levels (18ºC–20ºC). Several temperature, heat flux and solar radiation sensors were used. The outdoor air temperature and the solar radiation were inserted in the weather file (.epw) and the precipitation and irrigation were introduced directly in the program as schedules. Several experimental data was compared with simulation results, but in this document only the exterior soil surface will be examined since this parameter has already been used as a comparison factor for calibration purposes in several works [2, 5, 11, 23]. The authors used the numerical tools mean bias error (MBE) (Equation (1)) and root mean square error (RMSE) (Equation (2)) to execute an error analysis and determine the quality of the simulation results, the same instruments applied in this study. The 2015 summer campaign occurred between June 19th and 29th, while the 2016 summer campaign took place between July 16th and 25th. The 2016 winter campaign happened between February 3rd and 10th. It is important to observe that in the winter campaign the study period in trays T3 and T5 does not correspond exactly to the one in the other two trays.

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

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

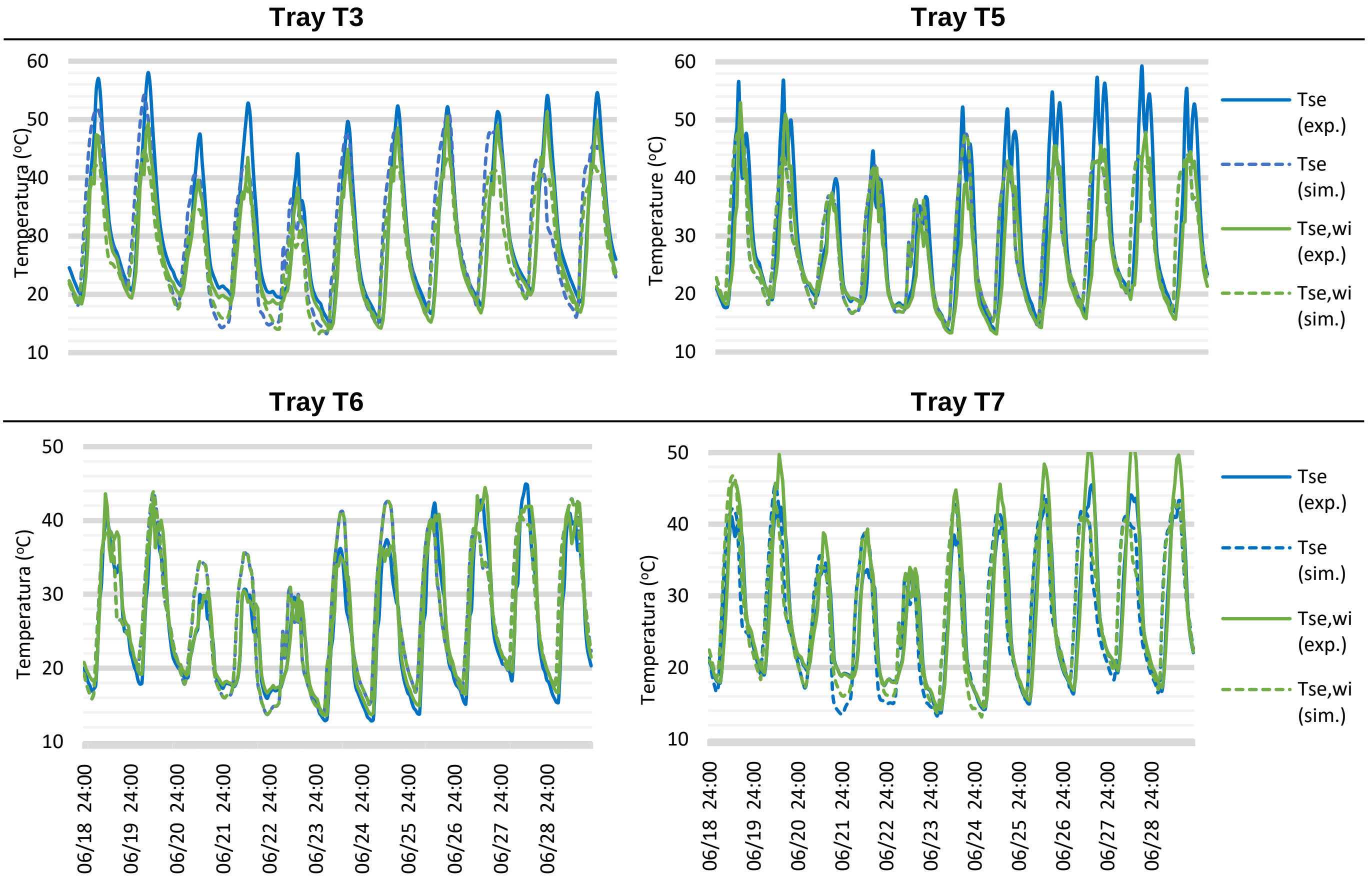

Figure 2 – Calibration results for the 2015 summer campaign

This fact was due to an experimental setback related with the measuring equipment in trays T3 and T5 which had to be fixed during the campaign. The measurements started only the 5th at 7pm. Figure 3, Figure 4 and Figure 5 illustrate the development of both surface outside temperatures (measured and simulated) through time in the 3 campaigns. Table 3 shows the values obtained for the error analysis parameters MBE and RMSE which are similar to those obtained in previous studies. It was concluded that the model represents the thermal behavior of the green roofs in a general way, except for some peak values which could be explained by the LAI parameter adopted, leaf reflectivity assumed for the model or solar absorptance of soil. Experimental errors should not be ignored at this point.

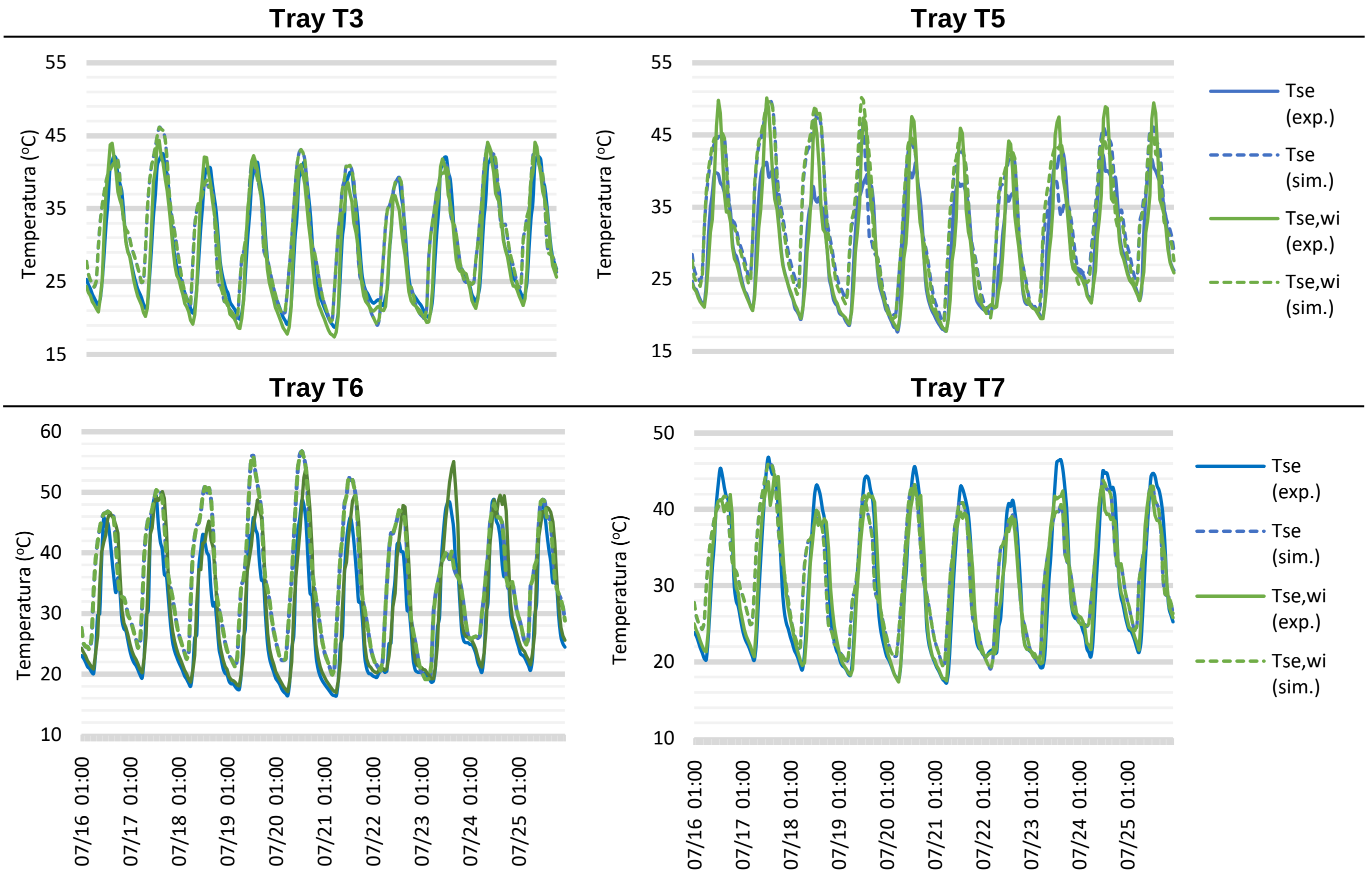

Figure 3 – Calibration results for the 2016 summer campaign

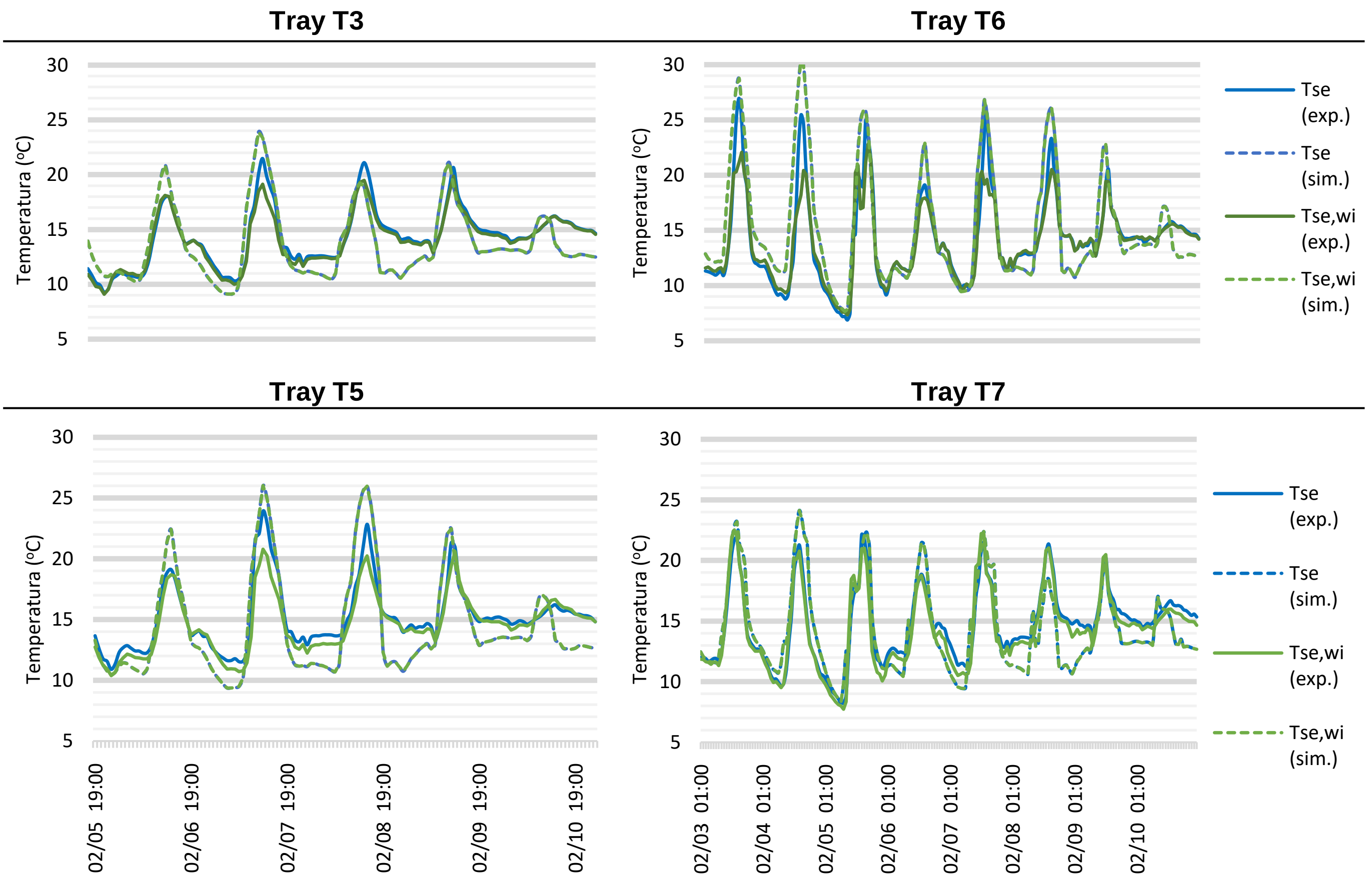

Figure 4 – Calibration results for the 2016 winter campaign

Table 3 – Values of error obtained compared to previous studies

Campaign	Tray	Parameters	Ti	Tsi	Tsi,wi	Tse	Tse,wi	Fsi	Fsi,wi
Ouldboukhitine, Belarbi and Sailor (2014)		MBE	-	-	-	1	-	-	-
		RMSE	-	-	-	-	-	-	-
Sailor (2008)		MBE	-	-	-	2,9	-	-	-
		RMSE	-	-	-	4,1	-	-	-
Summer 2015	T3	MBE	1,69	0,61	2,06	0,54	0,6	-	-
		RMSE	2,78	2,72	3,04	6,95	5,08	-	-
	T5	MBE	1,12	1,01	1,45	-0,34	2,92	0,52	0,94
		RMSE	1,79	2,08	2,34	7,02	6,68	3,51	1,63
	T6	MBE	-0,72	-1,65	1,28	2,21	1,13	-	-
		RMSE	1,62	2,54	1,94	4,62	4,49	-	-
	T7	MBE	-0,07	0,21	1,33	0,65	1,8	-2,47	-0,22
		RMSE	1,43	2,07	2,13	5,87	7,35	6,11	1,66
Summer 2016	T3	MBE	0,53	1,04	1,09	1,91	2,39	-	-
		RMSE	1,36	1,49	1,9	4,23	4,1	-	-
	T5	MBE	0,06	0,11	1,61	3,02	4,55	1,94	1,22
		RMSE	2,7	1,51	2,88	5,01	6,97	5,27	2,92
	T6	MBE	1,25	1,37	1,57	5,94	3,85	-	-
		RMSE	1,46	1,94	2,85	7,63	7,07	-	-
	T7	MBE	0,61	1,44	2,37	1,21	1,17	-1,19	0,4
		RMSE	2,32	1,71	3,13	4,31	3,78	3,12	1,83
Winter 2016	T3	MBE	-0,6	-0,6	-0,66	-0,62	-0,36	-	-
		RMSE	0,96	1,14	1,07	1,98	1,98	-	-
	T5	MBE	-0,44	-2,6	-1,67	-0,73	-0,22	-10,5	-3,78
		RMSE	1,14	2,76	1,78	2,16	2,42	11,45	3,99
	T6	MBE	-1,21	-1,7	-1,44	1,08	1,28	-	-
		RMSE	1,54	2,19	1,87	2,73	3,22	-	-
	T7	MBE	-0,62	-2,03	-1,43	-0,33	-0,02	-9,43	-3,87
		RMSE	0,94	2,19	1,58	2,03	1,91	10,26	4,05

5 Discussion and Analysis of Results

Since the trays were only an experimental base, it was necessary to choose a real building to conduct a more realistic study. A sound technical room was chosen because it had been intensely studied by Silva [5], who performed several simulations in this room.

5.1 Sound Technical Room

In this study an annual simulation is performed applying the characteristics of the trays – T3, T5, T6 and T7. According to Portuguese thermal regulation [24] the annual energy use was calculated considering multi-split air conditioning system of class B with COP=3.40 and EER=3.00 for heating and cooling seasons, respectively. The results obtained were then compared to those obtained by Silva [5], who created several green roofs, two of them very important for this study: reference and semi-intensive. Results are presented in Table 4. It is important to refer that all the characteristics of Silva´s [5] simulations were maintained, including materials, schedules and outside climatic conditions in order to obtain valid results. The only alteration was the green roof composition. This study was conducted with absence of thermal insulation. This information shows that the characteristics assumed for T5 and T6 are well suited for the heating season since they present the best results of all green roofs. For the cooling season T3 and T7 exhibit the lowest energy consumption even when compared to Silva´s [5] green roofs. In a global analysis, for the climate of Lisbon, the green roofs T3 and T7 reveal to be the most economical in a one year study. The justification for this behavior will be described with higher level of detail in the next paragraphs.

Table 4 – Energy needs for the green roofs created by Silva, M. F. (2014) and for T3, T5, T6 and T7

		Gulbenkian – Sound technical room				
		Energy needs (kWh/year/m^2)				
Silva (2014)		Heating	Cooling	Total	XPS = 0 (cm)	Roof Irrigation = 6 (mm/day active all year when soil humidity level <=40%)
	Reference	16,2	25,2	13,2		
	Semi -Intensive	19,4	19,7	12,3		
Trays	T3	18,7	13,3	9,9		
	T5	14,7	22,0	11,7		
	T6	14,0	26,1	12,8		
	T7	16,4	14,4	9,6		

5.2 Sensitivity Analysis

In this analysis only one of the parameters – LAI, height of plants, soil thickness and roof irrigation – will vary in each simulation, so that one can conclude about their single influence in energy performance.

5.2.1 LAI

The increase on LAI leads in all cases to a decrease in energy consumption (Figure 6). In winter it is harmful, but it largely compensates in summer, so there are savings for all trays in an annual based analysis. It is important to observe that the relative increase was not the same in all four trays according to Table 5.

Table 5 – Relation Savings / LAI increase

Tray	Energy Savings			LAI Increase (%)	Relation (Annual Savings / LAI Increase)
	Heat.	Cool.	Annual		
T3	19	-43	-7	200	-0,033
T5	47	-74	-26	313	-0,082
T6	57	-79	-32	385	-0,082
T7	25	-50	-10	217	-0,046

Observing Table 5 one can conclude that T5 and T6 had the greatest increases according to the last column. This relation demonstrates that the increases above LAI=2 are not as relevant as the ones below.

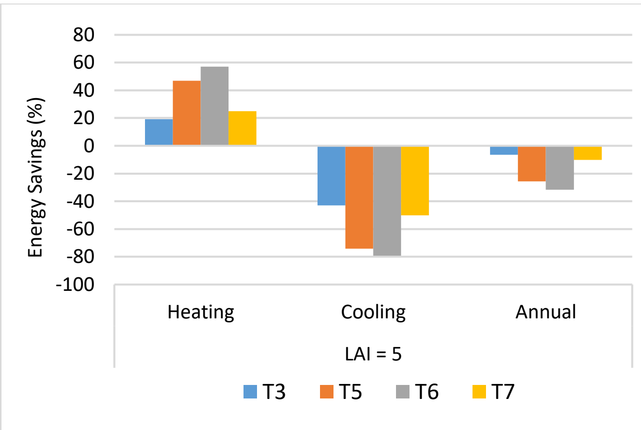

Figure 5 – LAI results

This fact indicates that LAI=2 represents a good reference value for energy savings in a city with a climate like Lisbon.

5.2.2 Height of plants

In relation to height of plants in can be referred that an increase in this parameter leads to energy loss when an annual analysis is conducted according to Figure 7. The response in each season is the expected – an increase in winter and a decrease in summer.

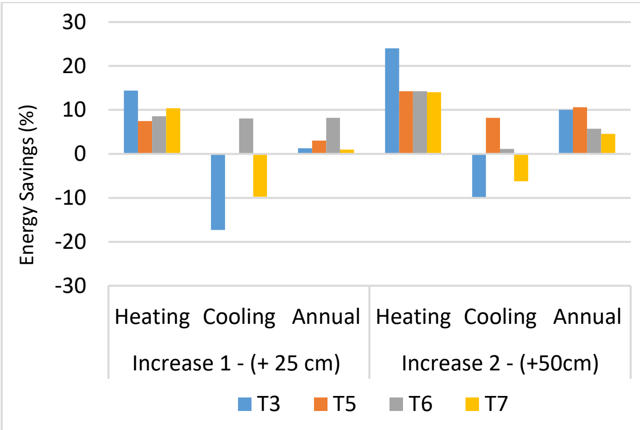

Figure 6 – Height of plants results

Only T5 and T6 had a non-expected performance in summer. The reason found for this fact is the influence of the LAI parameter. If there is a high value of LAI associated with higher plants, this leads to facilitation of the process of evapotranspiration but happening the opposite for low values of foliage density. This behavior was not expected according to previous works [2, 5, 23] but it is important to highlight that these results are only valid for the conditions assumed in the simulation – plants, soil and climate.

5.2.3 Soil thickness

For all the simulations the energy consumption in an annual based analysis decreased when the soil thickness was increased. By observing Figure 8 it can be concluded that the greatest achievements are recorded in the winter. For trays T5 and T6 a different performance occurred in summer from what was expected according to other studies [2, 5, 23].

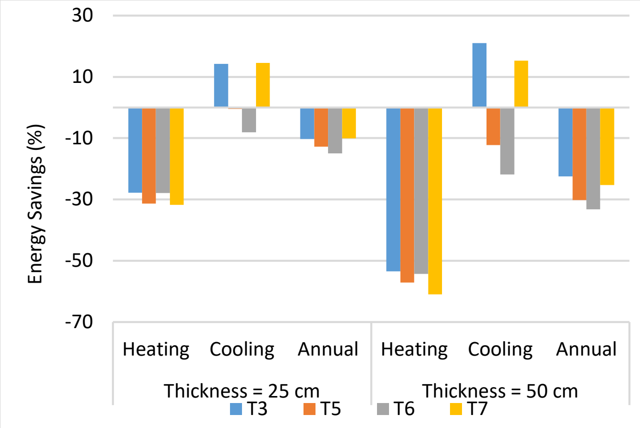

Figure 7 – Soil thickness results

In this season an increase in consumption was expected. This was due to the fact that the program assumed for the trays with low LAI that the superior thermal insulation provided by the soil would prevail over the higher difficulty in accomplishing the process of evapotranspiration.

5.2.4 Roof Irrigation

In this analysis it is important to refer that an annual irrigation schedule was used – Smart Schedule – which was active whenever the soil humidity was inferior to 40%.

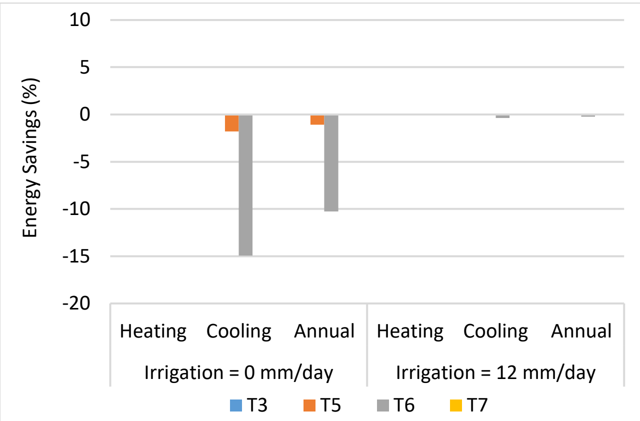

Figure 8 – Roof irrigation results

Results show that this factor is very important in summer. The data in Figure 9 demonstrates that no alterations were registered in T3 and T7. This fact may be due to higher foliage density in these trays which "protects" the soil layer from solar radiation, preventing accelerated dehydration of the substrate. This way the soil can conserve a larger amount of water and therefore not so dependent of daily irrigation. In the other trays – especially T6 – one can conclude that energy savings obtained with the use of 6 mm/day – 10% – led to superior values when compared to 12 mm/day which did not improve significantly the energy saving – inferior to 1%. This is an indicator that for the climate of Lisbon 6 mm/day represents a good value. This fact is consistent with previous studies [2, 5].

5.3 Density of dry soil

Trays T3 and T7 have almost the same characteristics in vegetation but a different soil composition. T3 has a density of 883 Kg/m^3 and T7 of 383 Kg/m^3. In this analysis both trays presented the same behavior in summer and winter, and similar savings in a one year analysis. It was concluded that density of dry soil has a reduced influence when compared to the other four parameters.

5.4 Comparison with conventional flat roofs

The majority of flat roofs in Portugal is non-accessible type where the superior layer is the protection layer, composed by a bituminous membrane. According to other studies [7] it is common to use the concept of white and black roofs which represents high and low values of albedo respectively. The method is the same as for all other simulations, but in this case the green roof is replaced by a black or white roof as the superior layer of the roof. The characteristics considered for the white and black roof are presented in Table 6. The results obtained are shown in Figure 10.
In sum the studied cases were:

- 4 semi-intensive green roofs – T3, T5, T6, T7
- 2 common roofs – black and white

Table 6 – Characteristics of the flat roofs

Material	White Roof (5mm)	Black Roof (5mm)
Rugosity	Medium Smooth	Medium Smooth
Thickness (m)	0,005	0,005
Thermal Conductivity (W/(m.ºC))	0,23	0,23
Density (kg/m^3)	1050	1050
Specific Heat (J/(kg.ºC))	1510	1510
Thermal Absorptance	0,9	0,9
Solar Absorptance	0,4	0,8
Visible Absorptance	0,4	0,8

XPS

The thickness of XPS was also evaluated. This material is used for thermal insulation so it is important to analyze its influence in both common and green roofs and that is why each comparison is made for the same level of insulation. It is important to refer that XPS will be positioned right below the protection layer – either common or green roof – so it does not influence the reflectivity of the analyzed roof. Observing Table 7 it can be concluded that the increase in XPS always leads to annual energy savings. In other words, more thickness provides greater savings.

Table 7 – Energy needs in the sound technical room for several levels of XPS

	Energy needs (kWh/year/m²)																	
	T3			T5			T6			T7			White Roof			Black Roof		
XPS (cm)	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total	Heat.	Cool.	Total
0	18,7	13,3	9,9	14,7	22,0	11,7	14,0	26,1	12,8	16,4	14,4	9,6	60,5	13,3	22,2	33,5	59,6	29,7
2	12,2	13,0	7,9	9,1	19,4	9,1	8,8	22,4	10,1	10,3	13,8	7,6	30,3	10,8	12,5	18,0	34,1	16,7
4	8,5	13,2	6,9	6,2	18,0	7,8	6,1	20,3	8,6	7,1	13,6	6,6	19,8	10,9	9,5	12,0	27,6	12,7
6	6,3	13,3	6,3	4,6	16,9	7,0	4,5	19,1	7,7	5,3	13,5	6,1	14,5	11,0	7,9	8,9	24,2	10,7
8	5,0	13,3	5,9	3,6	16,4	6,5	3,6	18,2	7,1	4,2	13,5	5,7	11,3	11,3	7,1	6,6	22,2	9,3

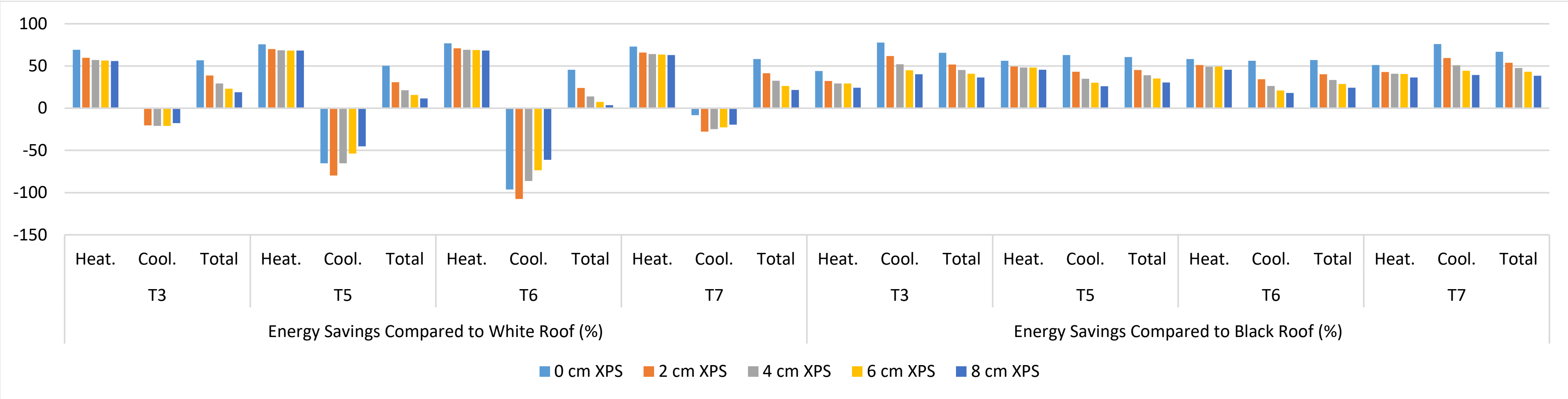

Figure 9 – Energy Savings obtained in the four trays compared to white and black roof

In the heating season the increase in XPS thickness always corresponds to energy savings which was expectable. In the cooling season the increase in XPS leads to great energy savings in T5 and T6 – low foliage density – less significant for high thicknesses, the same occurring in the black roof. For T7 there is always savings but less significant when compared to T5 or T6. T3 and the white roof have approximately the same performance, obtaining the highest savings for 2 cm of XPS.

White and black roofs

In the heating season green roofs demonstrate better performance when compared to white or black roofs according to Figure 9. This fact is due to the soil layer which increases the thermal insulation of green roofs and does not exist in the adopted conventional roofs. In this season savings vary between 77% for T6 without insulation compared to white roof and 24% for T3 compared to black roof with high level of insulation.

In the cooling season the green roofs performed better than the black roof due to the positive effect of evapotranspiration in green roofs and the negative effect of the dark color in the black roof. These savings fluctuate between 18% for T6 with high insulation to 78% for T3 without insulation. When the comparison is relative to the white roof the situation is altered. Neither of the green roofs can achieve positive savings when compared to the white roof due to its high albedo. The values of saving are in the interval of -107% for T6 with 2 cm XPS to 0% for T3 without insulation. It is important to highlight that in an annual based analysis all the green roofs performed better than any of the conventional roofs. In sum T3 and T7 are the ones that perform better in a one year study even for low level of insulation or absence. This fact occurs due to possessing the same thermal insulating properties in winter that T5 and T6 while benefiting the positive effects of higher LAI and leaf reflectivity in summer that decrease significantly the energy demand. In relation to white roof the main difference occurs in the heating season because it has been proved that the last one is the best performer in summer. These facts indicate that green roofs must be especially efficient in colder climates. It is important to refer that in the analyzed compartment – technical sound room – was considered to exist thermal transfers only by the roof as all the other surfaces were adiabatic. Since the roof usually only represents a fraction of thermal exchanges it is important to understand that the values of savings obtained in this work may have a different relative weight on other cases considering all the remaining surfaces thermal transfers.

6 Conclusions

The accomplishment of this work allowed to understand better the energy performance of a semi-intensive green roof. In the sensitivity analysis the main conclusions obtained were:

- The LAI parameter was favorable in energy savings for all the annual simulations conducted in the work. Harmful in winter but largely compensating in summer. LAI=2 is suggested to be a good value for the climate of Lisbon.
- The increase in soil thickness led to energy annual savings in all green roofs. In the heating season all four trays presented savings due to the increase on thermal insulation provided by the extra thickness of soil. In the cooling season T3 and T7 exhibited the expected performance – higher energy demand – but T5 and T6 revealed energy saving in this season – which in a certain way goes against the conclusions obtained by [2] and [5]. This fact was attributable to the low density of vegetation – LAI – which the program assumed the green roof to take no advantage in the process of evapotranspiration. Therefore it considered the thickness increase provided added thermal insulation and consequently energy savings.

- An irrigation of 6 mm/day reduced significantly – about 10% - when compared to the situation without irrigation and 12 mm/day did not produce any additional effects. This fact was clearer in T6 and T5 – low value of LAI.
- The height of the plants presented a similar behavior as the soil thickness parameter but in a reverse way, i. e, its increase was harmful in winter for all cases but benefic in summer for T3 and T7 which respects the conclusions of previous studies [2, 5]. T5 and T6 presented higher energy demand in summer which can only be attributable to the reduced foliage density and leaf reflectivity – only differences for T7 – which in these cases made evapotranspiration process more difficult.
- The soil density demonstrated a very small impact in energy performance

In the second phase of the study a comparison between green roofs and common flat roofs was conducted and also evaluating the influence of thermal insulation. It was concluded that the increase in the thickness of insulation – XPS – always led to greater energy savings except for T3 and the white roof, where the best performance was achieved for 2 cm XPS thickness. Specifically about the roof solution, it was possible to understand that the black roof presents the worst energy performance for the climate of Lisbon. The white roof was superior to all green roofs in a summer analysis for any level of insulation. It is important to refer that any of the four green roofs achieved better annual performance than the black roof which reinforces the belief on its excellent performance in cold climates. The best performances were achieved by T3 and T7, followed by T5 and T6. The larger savings were obtained for the solution without insulation. This fact indicates that the green roof solutions T3 and T7 are a good option for retrofitting old buildings in cities whose climate is similar to the Lisbon with preference for T7 because the soil layer density is lower.

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