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Energy Efficiency Evaluation of Green Roofs as an Intervention Strategy in Residential Buildings in the Field of Spanish Climate

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Abstract: The use of green roofs entails environmental, economic and social benefits as sustainable tools of architecture. They present proven benefits in the path towards carbon neutrality and the reduction of the consumption of energy resources, especially in the field of renovation and improvement of the thermal envelope. In Spain, the current climate crisis also implies a problem of water stress, so it is necessary to analyse in more detail the behaviour of self-sustaining green roofs in the different climatic and rainfall zones into which the territory is divided. Evapotranspiration is the main mechanism of heat dissipation in green roofs, but in this study, it is observed that in the case of self-sustaining roofs with limited water content, the greatest losses through evapotranspiration occur in climates with high temperatures and solar radiation, above cities with higher rainfall and colder climates. On the contrary, the greatest energy savings are obtained in this type of cold climate. Evapotranspiration in self-sustaining roofs is not the most determining factor for achieving energy savings. The design of the roof, the geometry and orientation of the building, as well as the cooling energy consumption, play a more determining role.

Keywords: green roof; self-sustaining; renovation; energy savings; temperature; solar radiation; rainfall; evapotranspiration

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1. Introduction

The progressive introduction of environmental concerns in the field of architecture, related to sustainability, reduction of energy consumption and carbon neutrality has been observed in the change of constructive strategies' direction. Both from the architectural design and from the current standard framework, an adaptation is produced to achieve the targets established in the 17 Sustainable Development Goals (SDGs) or flagship areas of the European Union (EU) [1]. All this is included in the different political agendas of the EU countries, such as the *Agenda 2030* in Spain [2]. Specifically, the EU has proposed to reduce greenhouse gas emissions by 40% and improve energy efficiency by 32.5% by 2030 [3]. In the specific case of Spain, the building sector already consumes 30% of the total energy, and more than half is the responsibility of the residential sector [4,5]. Considering that, it is understood that in order to meet these goals it is necessary to go through sustainable architecture.

The continuous updates of the construction standards of Spain are aimed at improving the thermal envelope, trying to increase the thermal inertia of the construction elements and reducing the air infiltrations that occur through them as much as possible. These air infiltrations are responsible for between 10% and 50% of the total energy consumption of a building [6]. However, it should be noted that, of the current housing stock, almost 6 million buildings are built before 1980 [7]. These buildings were designed and built without thermal insulation in the envelope since the first standard that introduced thermal concepts in buildings in Spain was the la *Norma Básica de la Edificación sobre Condiciones Térmicas* (NBE-CT-79), which came into effect in 1979 [8,9]. Approximately 60% of the buildings built and in use in Spain are prior to this standard and have not undergone any integrated renovation [5]. In this context, political and architectural efforts are aimed at promoting renovation, especially of this type of building, trying to support the sustainable race to achieve compliance with the goals of the *Agenda 2030* [10].

The range of tools provided by sustainable architecture to achieve these goals is very wide. Green roofs are presented as construction systems aimed at improving the insulation of the thermal envelope. However, they also influence basic aspects of sustainability, related to its three pillars: environment, economy and society. It is necessary to improve the energy performance of building, in addition to making them more resilient to climate change and contributing to reversing the environmental degradation of the urban context. A large number of studies have corroborated the environmental benefits of green roofs, such as the improvement of biodiversity [11,12], the reduction of the Urban Heat Island (UHI) effect [13,14], the pollution of the air [15], the runoff of rainwater [16,17], the improvement of the quality of this runoff [18] and the reduction of environmental noise [19,20]. In addition to different economic [21] and social [22] benefits, the improvement regarding the energy and thermal behaviour of the building must also be considered, thanks to factors such as the shade of the vegetation layer [23,24] or heat losses by evapotranspiration from the vegetation and substrate layers [25,26].

Regarding this last point, different investigations have confirmed that the energy savings produced by the installation of a green roof are more evident if they are applied in buildings whose previous thermic envelope had little or no insulation [27,28]. The conclusions obtained show that the savings produced with the installation of a green roof in a building whose envelope did not have previous insulation are much greater than in the case where the previous envelope is more and better insulated. Wong et al. [29] showed that for a roof with a transmittance of 0.51 W/m^2K, the annual cooling energy savings due to the installation of an extensive green roof was 0.6%, while the installation on a roof without prior insulation (and with a higher transmittance value) produced savings of up to 10%.

Therefore, the combination of environmental, economic and social benefits of green roofs make them stand out as highly appreciated tools of sustainable architecture. Even more due to the fact that the current actions are oriented towards the refurbishment of buildings, constructively and energetically obsolete, to promote their sustainable use. Green roofs perform better if their use is considered in these cases, so efforts should be directed towards promoting the installation of these systems in energy renovation projects for existing buildings.

The greatest environmental, energy and thermal benefits are obtained in intensive green roofs [30], in addition to allowing the use of these spaces as green areas or accessible gardens in the city [21]. However, these green roof systems present some problems related especially to their use in building renovations. The self-weight provided by intensive roofs is much bigger than in the case of extensive green roofs. The guide values of self-weight in a state of saturation for extensive roofs are between 60–180 kg/m^2, while intensive roofs would suppose an added load on the load-bearing structure of up to 600 kg/m^2 [31]. This implies a necessary study of the structural characteristics of the building to be renovated in both cases, and it will be highly probable that a structural reinforcement must be installed to support the loads provided by an intensive green roof (with the associated extra construction cost) [32].

From a climatic point of view, in Spain, the refurbishment faces problems derived from the climate itself. In general terms, Spain is one of the European countries with the lowest energy consumption in buildings, especially in the case of heating. This implies that the potential for energy and economic savings resulting from a thermal renovation of the envelope is much lower than in other EU countries [5]. This factor, added to the high cost of this type of intervention, even more in the case of installing innovative systems such as green roofs [33], makes it difficult to promote the improvement of the renovation of energetically obsolete buildings.

Different investigations have analysed the behaviour of green roofs in different climates [23,27,34]. Several factors, such as the type of vegetation, the Leaf Area Index (LAI), its height or the moisture content of the substrate play an important role, in addition to the type of climate, when determining the best energy performance of these roofs [16,30].

Therefore, this research proposes the study of three hypothetical situations of integrated renovation of the thermic envelope of a building without prior insulation, one of them with a traditional roof and two with a green roof. Both green systems will be designed as self-sustaining and each of them will have particularities regarding the vegetation and the substrate, thus analysing the behaviour of an extensive and intensive green roof.

The limitations of this study, which have focused on the thermal behaviour of self-sustaining green roofs and their contribution to the energy efficiency of the building, must be considered. The thermal performance of green roofs with irrigation, as well as the different environmental benefits of vegetated systems, are left out of the study. In addition, the heat transfer mechanisms in green roofs are complex, making it necessary to use simplified models.

The objective of this research will focus on defining which climatic variables (outdoor temperature, solar radiation and rainfall) are more decisive when it comes to obtaining energy savings after improving the thermal envelope of a building without previous insulation. In the specific case of green roofs, the main mechanism of heat dissipation (evapotranspiration) is studied in-depth, as well as which of these climatic variables is more influential. Finally, the magnitude of this phenomenon and its influence on energy savings for green roofs without irrigation (self-sustaining) will be analysed.

To do this, in the Materials and Methods section, eight Spanish cities are described, according to the six climatic zones and the five rainfall zones into which the territory is divided according to standards. The reference model that is intended to be renovated and the three renovation assumptions are detailed, whose construction and design particularities are described. Finally, the computer program to be used is presented: EnergyPlus.

Next, in the Results and Discussion, the energy savings obtained after the renovation with each of the three models are presented. The analysis of which climatic variables determine greater evapotranspiration in self-sustaining green roofs is deepened. Finally, the evapotranspiration values and the different climatic variables associated with each of the eight cities are related to the energy savings obtained to assess which ones have a greater influence. The reflections resulting from this study are presented in the Conclusions.

2. Materials and Methods

In order to cover the entire variety of climatic environments that exist in the Spanish territory, both on the peninsula and outside it, a selection of 8 cities is established that cover the 6 climatic zones and the 5 average rainfall zones (Figure 1 and Table 1). In accordance with the Spanish standard of buildings construction (*Código Técnico de la Edificación*, CTE), and the specific document about energy efficiency (*Documento Básido de Ahorro de Energía*, DB HE) [35], 6 climatic zones are identified based on outdoor temperatures and incident solar radiation, which serve as a reference for calculating the necessary insulation in the building envelope, both in new-build projects and in refurbishment. On the other hand, in the *Documento Básico de Salubridad* (DB HS) Spain is classified into 5 average rainfall zones based on the annual rainfall index [36]. The climatic zones are classified as α-A-B-C-D-E, with α being the characteristic climate of the Canary Islands, while on the peninsula the climates are classified from A, warmer, to E, colder. In the case of average rainfall zones, the following are differentiated, whose annual rainfall index (p) is indicated below: I ($p > 2000$ mm); II (2000 mm $\geq p >$ 1000 mm); III (1000 mm $\geq p >$ 500 mm); IV (500 mm $\geq p >$ 300 mm); V ($p < 300$ mm).

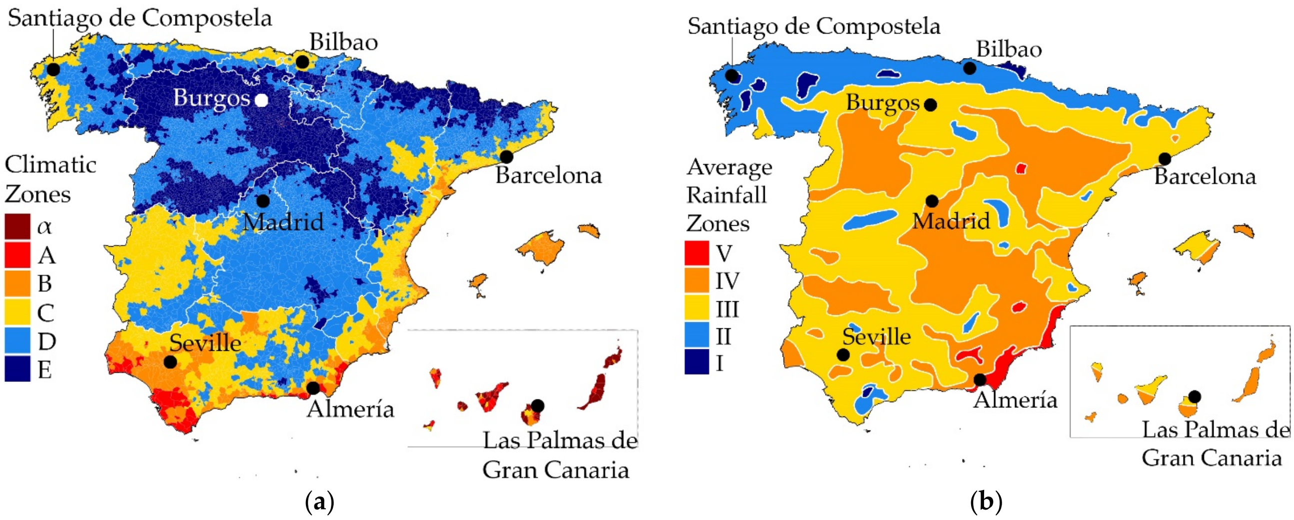

Figure 1. Location of cities and (**a**) climatic zones and (**b**) average rainfall zones.

Table 1. Climatic and average rainfall zones of each city. Thickness of the roof's insulation material layer.

City	Climatic Zone	Average Rainfall Zone	Insulation Material Thickness (cm)		
			A	B	C
Las Palmas de Gran Canaria	α	III	4.5	3.5	3.0 [1]
Almería	A	V	5.5	4.5	3.0 [1]
Seville	B	III	8.0	6.5	3.0 [1]
Bilbao	C	II	12.5	11.0	7.5
Barcelona	C	III	12.5	11.0	7.5
Santiago de Compostela	D	I	13.0	11.5	8.0
Madrid	D	IV	13.0	11.5	8.0
Burgos	E	III	15.5	14.0	10.5

[1] Minimum thickness of the insulation material layer on green roofs.

In each of these cities, the design of a single family attached house (Figure 2) is proposed in accordance with the construction and structural system of the 1950s and 1960s in Spain. Therefore, being a construction prior to 1980, it does not have any type of insulation in the thermal envelope. The integrated renovation of the building envelope is proposed in all cities, adjusting in each of the 8 cases the level of insulation necessary to meet the requirements of the standard [35]. Focusing attention on the roof construction system, in each of the locations the thickness of insulating material has been calculated (Table 1). It can be seen that, in no case, a green roof will be laid out without a layer of insulating material, despite the fact that the substrate layer itself complies with the thermal requirements of the standard for each thermal zone. In these cases, a minimum thermal insulation layer of 3 cm is available, since thermal bridges can occur in the substrate, or variations in thermal conductivity, depending on the amount of water it stores [32].

For the 8 cities, the refurbishment of the entire thermal envelope (facade, slab on grade, party wall, windows and roof) is proposed, varying the roof construction system used. Therefore, three renovation models are proposed that represent a traditional roof with a gravel finish (A), an extensive green roof (B) and an intensive green roof (C) (Figure 3). In this case, the comparison of the energy behaviour after the integrated renovation with each roof model is proposed. A comparison will be made regarding a building without any type of previous insulation (reference model), carrying out an energy simulation for each city (with its respective climatic characteristics [37]) for a whole year (2021).

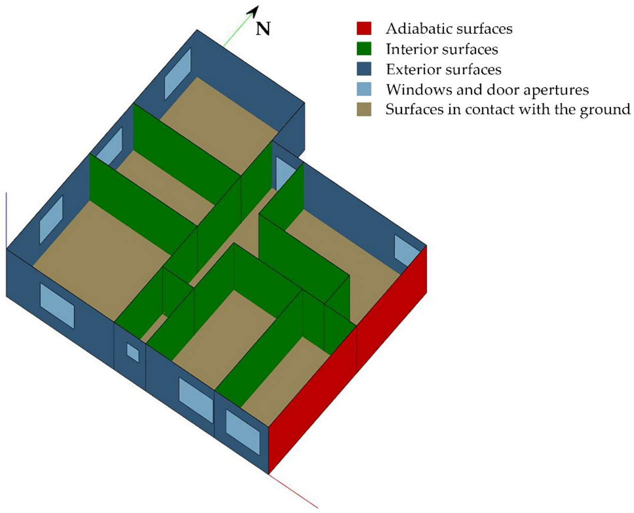

Figure 2. Single family attached house model and type of surfaces.

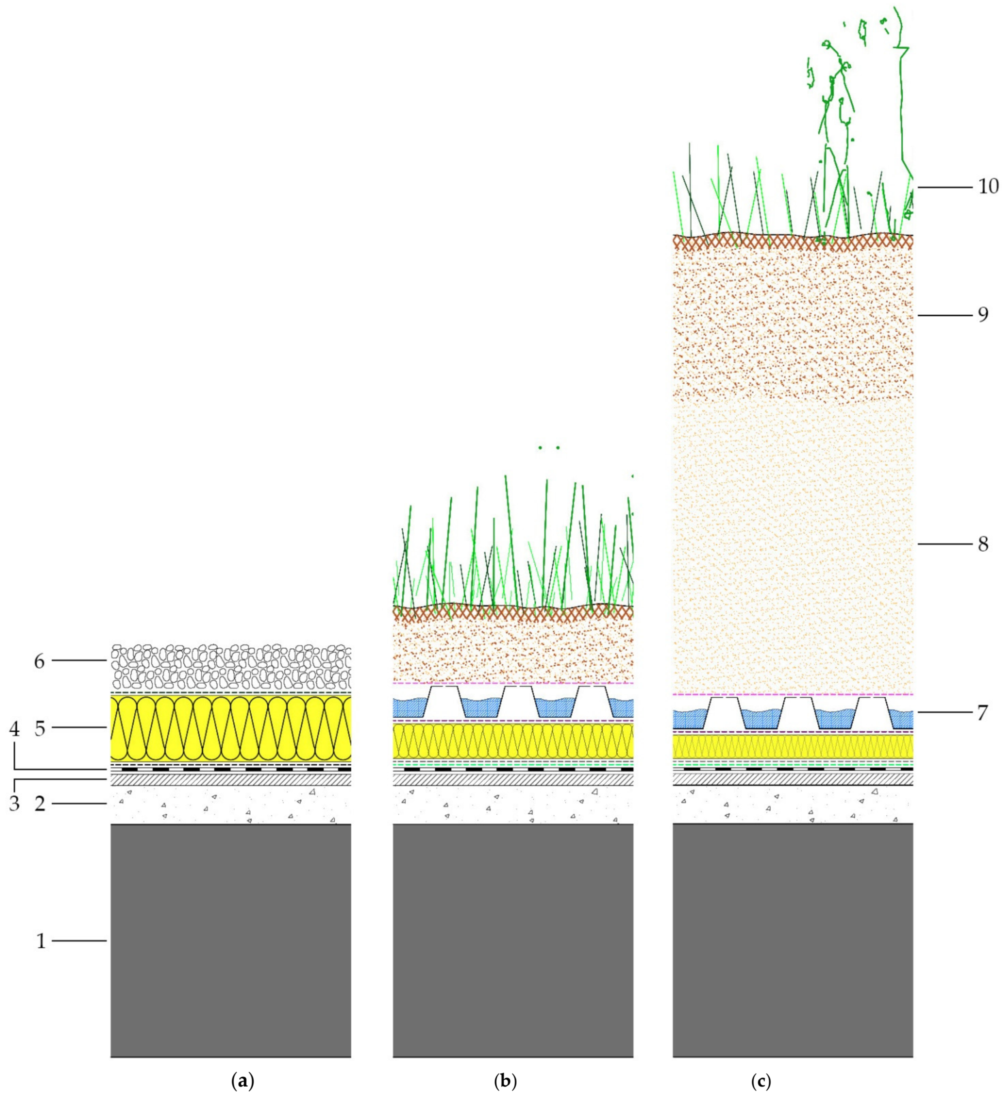

Figure 3. Roof models proposed for refurbishment: (**a**) traditional with gravel finish; (**b**) green extensive; (**c**) green intensive. Legend: (1) Support structure; (2) Slope formation; (3) Regulation mortar; (4) EPDM waterproof sheet; (5) XPS thermal insulator; (6) Gravel; (7) Drainage layer + Filter sheet; (8) Inorganic substrate; (9) Organic substrate; (10) Vegetation.

Without neglecting other important aspects in the field of refurbishment, such as the self-weight provided by the new roof system, an analysis of the load provided by each of the models has been carried out. The maximum thickness of thermal insulation in each of the models (climate zone E) and maximum water saturation in the substrate and water storage layers have been considered. In this context, the loads provided by the waterproof sheet and the upper layers after a renovation are calculated, considering that the slope formation is maintained because it is in good condition. The result is 162.39 kg/m^2 for model A, 208.05 kg/m^2 for model B, and 981.5 kg/m^2 for model C. Since the reference model is assumed to be built in the 1950s and 1960s, an approximation to the structure calculation of the roof is made based on the standards valid at that time. It is the *Norma M.V. 101-1962 de Acciones en la edificación*, passed in 1963 and first standard relative to the structure calculation in the buildings, and the *Instrucción para el proyecto y la ejecución de obras de hormigón en masa o armado* (EH-68), passed in 1968 that introduces magnification factors for loads in concrete. In this context, it was considered that the live load in a private access roof was 150 kg/m^2, and the magnification factor is 1.5. Therefore, the roof structural system of the reference model could withstand an overload of up to 225 kg/m^2, with models A and B below this limit. In the case of model C, the greater thickness of the substrate and weight of the vegetation implies an increase in the load well above 225 kg/m^2. A detailed structural study is always necessary for each building, but in general terms, it is observed that structural reinforcement would be necessary for an intensive system.

To carry out the study of the annual energy behaviour, the EnergyPlus thermal balance calculation engine, developed by the United States Department of Energy (DOE), has been used. This engine was chosen as it is an open-source simulation tool that is constantly being improved and updated, which is why it is considered one of the most adaptable energy calculation programs [38,39]. In Spain, it is necessary to carry out an evaluation of the energy efficiency of any building project to build, renovate, buy or sell. To carry out this evaluation, one of the official programs can be used, such as, for example, the *Herramienta Unificada LIDER-CALENER* (HULC) or one of the reference calculation engines recognized by the Spanish standard, among which is EnergyPlus [40].

To facilitate the 3D design of the building, as well as the introduction of variables (climatic data, types of materials, internal loads, thermal zones, etc.), a graphical interface designed specifically for this calculation engine has been used: OpenStudio (designed by the DOE itself and that allows the 3D design of the building using SketchUp [39,41]).

EnergyPlus is widely used in this field of research. It integrates the green roof calculation model implemented by Sailor [42], based on the FASST (Fast All-season Soil STrength) model developed by Frankenstein and Koenig [43]. In this model, only two heat balances are considered: (i) surface between the substrate and the cover and (ii) surface between the substrate and the vegetation. According to Oldboukhitine et al., even though the model proposed by Sailor presents some simplifications, it considers sufficient thermal heat transfer phenomena between the components of the green roof (especially between the layers of vegetation and substrate, whose behaviour in relation to heat transfer is more complex) [44]. A large amount of research, after the development of this model by Sailor and its implementation in EnergyPlus, has verified the validity of this system [45–47].

For the modelling of the reference building in EnergyPlus and the subsequent renovations, it has been necessary to determine different parameters such as the transmittances of the construction systems of the envelope (Table 2) according to the limitations for each climatic zone.

In the case of green roofs, it is necessary to introduce a greater number of variables. For example, aspects such as LAI, leaf reflectivity, minimum stomatal resistance and the thickness of the substrate or its conductivity. For models B and C it is designed: (i) for the extensive cover (B) a substrate thickness of 10 cm and succulent vegetation, in this case, sedum [48]; (ii) for the intensive system (C) a layer of 60 cm deep substrate with vegetation of evergreen and turfgrass herbaceous species, specifically from the gramineous family. Table 3 summarizes the main values for the design of roofs A, B and C [34,49,50].

Table 2. Thermal transmittance (W/m^{2}K) of the envelope's elements in the reference model and in the renovation proposed with models A, B and C.

	Reference Model		Renovation Models					
			α	**A**	**B**	**C**	**D**	**E**
Facade	3.018		0.560	0.500	0.380	0.290	0.270	0.230
Roof	1.404	Model A	0.485	0.423	0.320	0.223	0.216	0.185
		Model B	0.474	0.414	0.330	0.228	0.220	0.189
		Model C	0.320	0.320	0.320	0.223	0.215	0.185
Slab on grade	5.253		0.800	0.800	0.690	0.480	0.480	0.480
Party wall	2.520		0.900	0.800	0.750	0.700	0.650	0.590
Window (glazing + frame)	5.689		0.999	0.999	0.999	0.999	0.999	0.999
Front door	4.200		4.200	4.200	4.200	4.200	4.200	4.200

Table 3. Main characteristics of the three roof models' finishes proposed for renovation.

		A	**B**	**C**
Vegetation typology			Sedum	Gramineous
	Height of plants (m)		0.10	0.40
	Leaf Area Index (LAI)		0.80	5
	Leaf reflectivity		0.22	0.30
	Leaf emissivity		0.95	0.95
	Minimum stomatal resistance (s/m)		300	120
Soil typology				
	Thickness (m)		0.10	0.60
	Conductivity of dry soil (W/mK)		0.435	0.435
	Density of dry soil (kg/m^3)		940	940
	Specific heat of dry soil (J/kgK)		1420	1420
	Thermal absorptance		0.90	0.90
	Saturation volumetric moisture content (soil layer)		0.40	0.50
Gravel				
	Thickness (m)	0.06		
	Conductivity (W/mk)	2		
	Density (kg/m^3)	2200		
	Specific heat (J/kgK)	1180		
	Thermal absorptance	0.90		

In relation to the interior of the house, it consists of a dining room, kitchen, bathroom, master bedroom, 2 single bedrooms and a study, so it is considered that 4 people live there, 2 adults and 2 children/youngster. These spaces are divided into 5 thermal zones, and for each of them, natural ventilation is established according to standards [36]. The values are expressed in Air Changes per Hour (ACH), and only the corridor does not have natural ventilation, as it does not have windows to the outside. Both the description of thermal zones and ventilation, as well as the internal loads (people taking up the room, lights and electric equipment) applicable to each space can be obtained from Table 4. Regarding air infiltrations, in the reference model it is higher, 0.7 ACH, while, after the renovation, by improving the insulation and construction systems of the envelope, this number is reduced to 0.1 ACH. Finally, as air conditioning systems are not the direct object of study in this research, it has been decided to select the Ideal Air Loads System, in which no dimensioning or specifications of the model chosen are required. Regarding the set-points, both for heating and cooling, they have been established at 21 °C and 25 °C, respectively.

Regarding the design particularities of the green roofs, in the two cases, a self-sustaining system is proposed [51]. Climate change also affects the global water cycle, increasing the contrast between dry and wet areas and seasons. In addition, it produces an increase in water stress. Spain is one of the European countries that suffer the most from this problem. In fact, between 2011 and 2040, 56.2% of the surface of the Spanish territory is at risk of desertification, a value that is estimated to rise to 71.3% by 2071–2100 if the current trend continues [52]. During the month of greatest water scarcity (July) the highest temperatures and solar radiation are recorded, so the need for water in the green roofs is also greater. In addition, over 80% of the population in Spain is in a situation of extreme water scarcity during this month [53]. All of this has the consequence that in times of drought the irrigation of urban green areas and gardens is usually cut back since this does not directly affect human consumption. Considering this problem, a balance must be found between increasing green areas to adapt to climate change and water scarcity [54]. Therefore, the design of green roof solutions that do not have an irrigation system (self-sustaining) can help to solve this problem.

Table 4. Internal loads of people, lights (W) and electric equipment (W) applicable to each room. Thermal zone with which each room is associated and designed with natural ventilation (ACH).

	People	Lights	Electric Equipment	Thermal Zone	Ventilation
Dining room	4	36 W	235 W	1	1.55 ACH
Kitchen	4	46 W	4750 W	2	1.90 ACH
Bathroom	1	18 W	-	3	7.82 ACH
Master bedroom	2	34 W	-	4	0.85 ACH
Single bedroom (2 units)	1	23 W	-	4	0.85 ACH
Study	2	36 W	180 W	1	1.55 ACH
Corridor	1	24 W	-	5	-

To achieve an improvement in the energy efficiency of the reference model, this research has focused on increasing the inertia of the building's thermal envelope and on the installation of green roofs. Within these vegetated systems, the evapotranspiration phenomenon is one of the main heat dissipation mechanisms in times of high temperatures and solar radiation [55]. In this way, heat transfers to the interior of the building and air conditioning consumption are limited.

The scarcity of water, with the consequent limitation of the humidity available in the substrate layer, will imply problems for the survival of the vegetation as well as a limitation of the phenomenon of evapotranspiration. The use of succulent species (model B) presents a better behaviour and survival against water stress than the rest of the species (model C) since they can regulate the opening of their stomata to lose less water by transpiration when there is little available [56]. This will imply that the behaviour of the self-sustaining green roof will not be the best that could be expected during hot seasons, since the limitation of available water will produce a decrease in cooling by evapotranspiration.

The evaluation of these self-sustaining systems in different climates will allow knowing their behaviour under different temperature and solar radiation conditions, as well as in areas with a different rainfall index, and therefore, different availability of water.

3. Results and Discussion

The evaluation of the energy behaviour of the different constructive solutions for the single family attached house model described above shows that energy savings are produced by improving the thermal envelope of the building (models A-B-C) in all the cities, with the exception of Las Palmas de Gran Canaria (Figure 4).

According to IDAE [57], the average values of total annual energy consumption of a single family house in Spain take the following values: (i) for a Mediterranean climate, 13,250 kWh; (ii) North Atlantic climate, 15,000 kWh; (iii) and Continental climate, 19,667 kWh. Figure 4 shows that the total annual energy consumption of the reference model fits these values. Almería, Seville and Barcelona are considered Mediterranean climates, Bilbao and Santiago de Compostela as North Atlantic climates and Madrid and Burgos as Continental climates. The climate of Las Palmas de Gran Canaria is not defined in the IDAE.

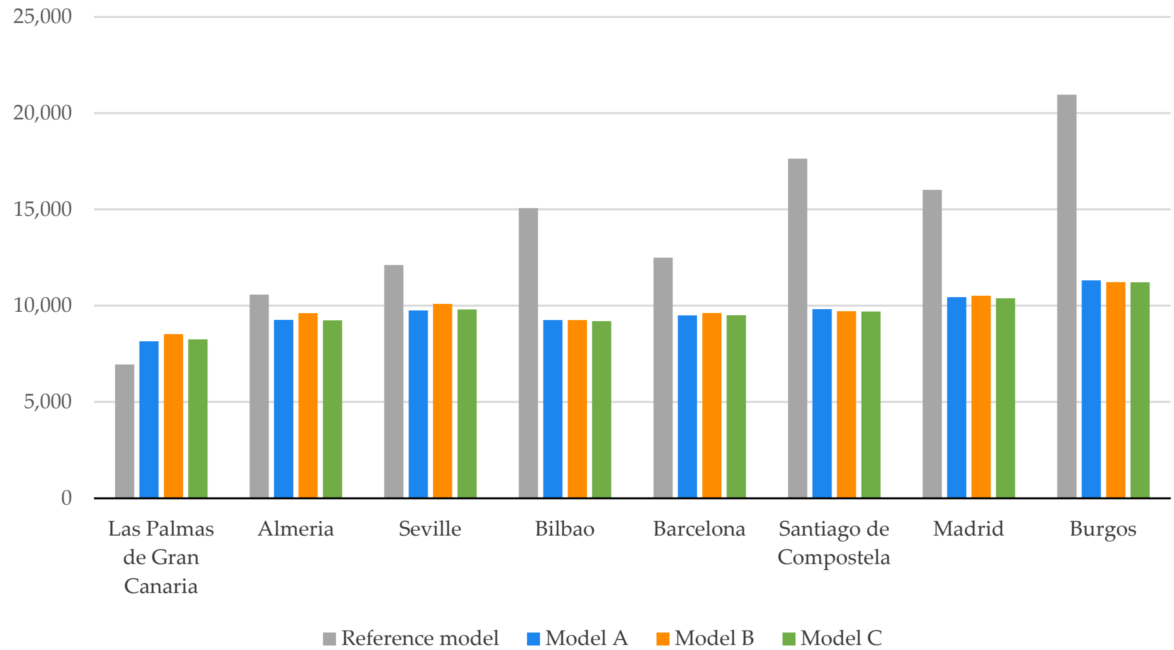

Figure 4. Total annual energy consumption (kWh) in the reference model (without insulation in the envelope) and the A-B-C renovation models in the eight cities.

Las Palmas de Gran Canaria has a climate with moderate temperatures that remain relatively stable throughout the year. It can be seen in Table 5 how the maximum and minimum annual average outdoor temperatures are 23.4 °C and 19.1 °C, respectively, and differ by 4.3 °C. According to current Spanish standards [58], the comfortable temperature inside a building is between 23 °C and 25 °C. Therefore, in this city, outside temperatures remain closer to the indoor comfort temperature, without so many annual or daily temperature fluctuations. That is why the reference model, without thermal insulation and with greater air infiltrations from the outside through the envelope, has lower energy consumption by taking advantage of these external privileged thermal conditions.

Table 5. Annual average hourly outdoor temperature (°C) for each city.

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Las Palmas de G.C.	19.7	19.6	19.4	19.3	19.2	19.1	19.1	19.6	20.6	21.6	22.5	23.0	23.3	23.4	23.3	23.1	22.7	22.1	21.3	20.7	20.4	20.2	20.0	19.8
Almería	17.6	17.3	17.0	16.7	16.5	16.3	16.4	17.0	18.2	19.8	21.0	21.8	22.3	22.6	22.7	22.5	22.1	21.5	20.6	19.7	19.0	18.5	18.2	17.9
Seville	16.6	16.0	15.5	15.1	14.7	14.4	14.3	14.8	15.8	17.5	19.3	20.9	22.4	23.5	24.1	24.9	24.9	24.4	23.4	21.9	20.3	19.3	18.3	17.3
Bilbao	12.6	12.4	12.2	12.1	12.0	11.8	11.9	12.4	13.3	14.7	16.1	17.2	17.9	18.3	18.4	18.2	17.7	17.0	16.0	15.1	14.3	13.8	13.3	12.9
Barcelona	16.1	15.8	15.5	15.3	15.1	15.0	15.1	15.5	16.3	17.1	17.9	18.6	19.0	19.3	19.3	19.2	18.9	18.5	18.0	17.5	17.1	16.8	16.6	16.3
Santiago de Compostela	10.6	10.3	10.1	9.9	9.8	9.8	10.0	10.7	12.0	13.2	14.3	15.6	16.2	16.5	16.8	16.5	15.8	15.0	13.9	12.8	12.1	11.5	11.1	10.8
Madrid	12.7	12.1	11.5	11.0	10.6	10.2	10.0	10.6	12.1	13.9	15.8	17.3	18.6	19.6	20.4	20.7	20.7	20.3	19.0	17.5	16.1	15.0	14.1	13.4
Burgos	8.5	8.2	7.8	7.5	7.3	7.0	6.9	7.4	8.6	10.1	11.7	13.2	14.4	15.2	15.8	16.0	15.8	15.1	14.1	12.7	11.3	10.2	9.4	8.9

blue = low temperatures, red = high temperatures.

It can also be seen how, except for the case of Las Palmas de Gran Canaria, the energy savings provided by the models with a green roof (B-C) are greater when compared to the reference model (without previous insulation in the envelope) than if compared to the energy consumption of these two models with model A (with a thermal envelope's transmittance lower than the limit established by the standard and with fewer air infiltrations). For example, in Almería, savings of 9.11% have been obtained for model B compared to the reference model in total annual energy consumption. On the other hand, with respect to model A, model B implies an increase in consumption of −3.78%. In the case of model C, the savings regarding the reference model are 12.63%, while regarding model A the savings are only 0.24%.

On the other hand, analysing the behaviour between the three models A-B-C, it is verified that the performance of models A and C is very similar, regardless of the city. The differences in the energy consumption of these two models range between −1.24% in Las Palmas de Gran Canaria and 1.24% in Santiago de Compostela. On the other hand, model B shows a more variable performance. This is due to a series of factors that make it more susceptible to outdoor temperature conditions, solar radiation and rainfall: (i) the substrate is thinner, so it stores less water available for vegetation and for evapotranspiration in the substrate layer; (ii) the vegetation is low and there is no air gap between the vegetal layer and the substrate in which the wind can dissipate the accumulated heat; (iii) the vegetation, being sedum succulent species, does not have a high LAI, so the shade produced on the substrate will be limited; (iv) this type of vegetation has the ability to regulate the opening of its stomata and limit heat losses by evapotranspiration in the vegetation layer during times of water stress. All these factors justify that, in cities such as Almería, Seville, Barcelona or Madrid, with hotter summers, intense solar radiation (Table 6) and little annual rainfall, the self-sustaining model B shows evidently worse energy behaviour than models A and C. On the other hand, in cities such as Bilbao, Santiago de Compostela or Burgos, with lower temperatures, less solar radiation and greater rainfall, this model B can even produce greater annual savings in total energy compared to the reference model than model A.

Table 6. Average annual hourly solar radiation (W/m^2) for each city.

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Las Palmas de Gran Canaria	0	0	0	0	0	0	0	10	94	298	482	589	646	659	662	660	612	491	290	92	7	0	0	0
Almería	0	0	0	0	0	9	174	384	600	688	721	729	713	678	617	519	360	179	52	4	0	0	0	0
Seville	0	0	0	0	0	0	131	328	524	641	678	687	675	645	596	518	387	222	76	6	0	0	0	0
Bilbao	0	0	0	0	0	19	120	234	360	437	466	477	469	443	394	318	223	127	46	7	0	0	0	0
Barcelona	0	0	0	0	0	48	179	324	484	562	594	599	582	545	481	373	240	118	33	3	0	0	0	0
Santiago de Compostela	0	0	0	0	0	2	98	222	344	441	458	454	437	412	370	295	188	88	24	2	0	0	0	0
Madrid	0	0	0	0	0	14	171	344	505	594	623	630	616	587	537	455	330	182	60	5	0	0	0	0
Burgos	0	0	0	0	0	14	125	252	387	481	517	527	517	490	444	367	264	153	57	9	0	0	0	0

blue = low temperatures, red = high temperatures.

If a comparison is made between extensive model B and intensive model C, it is observed that, in all the cities, except Las Palmas de Gran Canaria, model C has lower energy consumption. The greater thickness of the substrate layer, which provides greater inertia to the construction system, as well as the particularities of the vegetation justifies these values. Thanks to the high LAI of the vegetation chosen for model C, a greater shadow is produced on the substrate and a lower direct incidence of solar radiation. In addition, different investigations have related a higher LAI with higher evapotranspiration losses from the vegetation layer and, therefore, higher total evapotranspiration losses (substrate and vegetation) [13,55].

Due to the variation in the behaviour of model B, it is analysed in more detail which climatic variables have a greater influence on the energy savings obtained. Considering that, theoretically, the main cooling factor of the green roof is heat losses by evapotranspiration, the influence of the climatic or average rainfall zone in each of the cities is valued. From the point of view of rainfall, it can be seen in Figure 5 that as annual rainfall increases, fewer heat losses are produced by evapotranspiration in the extensive green roof. For example, in the case of cities such as Bilbao, Santiago de Compostela or Burgos, where it has been verified that there is a better energy performance of model B than of model A, it is observed that there are losses due to evapotranspiration below $-0.80\ W/m^2$. This occurs despite the fact that these cities are located in the highest average rainfall zones (II, I and III, respectively). Therefore, a higher content of available water in the substrate due to rainfall does not imply, by itself, higher heat losses through evapotranspiration in the self-sustaining extensive green roof.

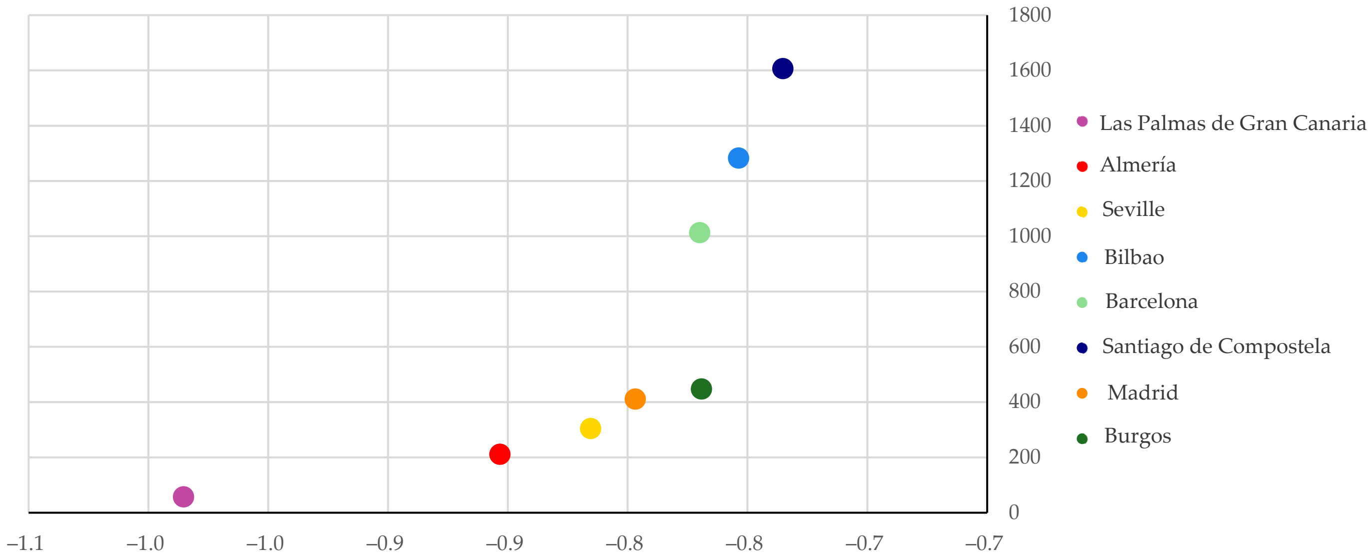

Figure 5. Heat losses due to evapotranspiration (W/m^2) in the extensive green roof of model B regarding annual rainfall (mm) in each of the 8 cities.

On the other hand, if heat losses through evapotranspiration are related to the mean annual outdoor temperature, a relationship is observed between the higher temperatures and the increase in heat losses through evapotranspiration (Figure 6). In this case, Las Palmas de Gran Canaria, Almería, Seville, Barcelona or Madrid have average annual outdoor temperatures above 15 °C, producing greater losses than in the case of cities with lower average annual outdoor temperatures. These cities also are the ones with higher annual rainfall. It can be seen how in addition, the decrease in the average annual temperature produces a decrease in losses due to evapotranspiration, especially in the gap between Las Palmas de Gran Canaria (average annual temperature of 20.95 °C) and the rest of the cities with average annual temperatures below 20 °C.

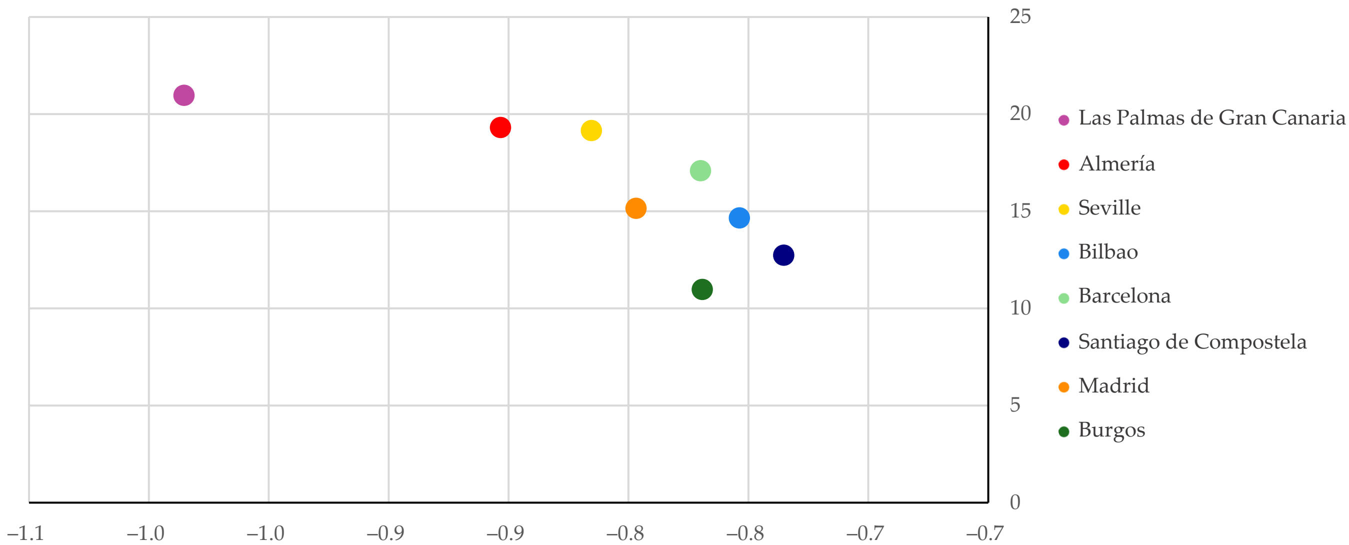

Figure 6. Heat losses due to evapotranspiration (W/m^2) in the extensive green roof of model B regarding the average annual temperature (°C) in each of the 8 cities.

Therefore, it is observed that the cities with the highest average annual temperatures and solar radiation are the ones that present the greatest heat losses due to evapotranspiration. This occurs at the expense of those cities in which the highest annual rainfall occurs. This indicates that heat losses by evapotranspiration in self-sustaining green roofs are more influenced by outdoor temperature and solar radiation. That is, in cities with high average annual outdoor temperatures and solar radiation, greater heat losses are produced by evapotranspiration, despite having less water available in the substrate and vegetation layer. This leads us to think that, if the annual rainfall of Santiago de Compostela were to occur in cities such as Almería or Seville, the available stored water would be greater and the losses due to evapotranspiration would be even higher.

Taking Madrid and Santiago de Compostela as an example, two cities in climate zone D, it is observed that Madrid has an average annual temperature of 2.42 °C higher and a maximum average annual direct solar radiation of 172 W/m^2 higher than Santiago de Compostela. In this case, the heat losses due to evapotranspiration in Madrid are −0.06 W/m^2 higher than in Santiago de Compostela, despite the fact that in this city the annual rainfall has been 1195.7 mm above the values for Madrid. Comparing the case of Bilbao and Barcelona (climatic zone C), it is observed that despite presenting a similar average annual temperature variation (2.43 °C), the lower variation of the maximum average annual direct solar radiation (122 W/m^2) the produced values of evapotranspiration losses in these cities are closer (−0.75 and −0.77, respectively, being higher in the city with the highest average annual temperature and maximum average annual solar radiation).

Once the variables that most influence heat losses by evapotranspiration have been determined, it can be verified in Figure 7 how the greatest losses do not imply greater energy savings with model B compared to the reference model. In this case, energy savings are more influenced by outdoor temperatures (Figure 8). On the basis of a building without previous insulation in the envelope, the energy savings obtained by improving the thermal envelope and installing an extensive green roof are greater in extreme and colder climates. The cities that present lower average annual temperatures, in addition to being those locations in which greater daily and annual thermal variations are observed (probably due to the fact that they are inland cities, without direct contact with the sea), are the ones that achieve the best energy savings.

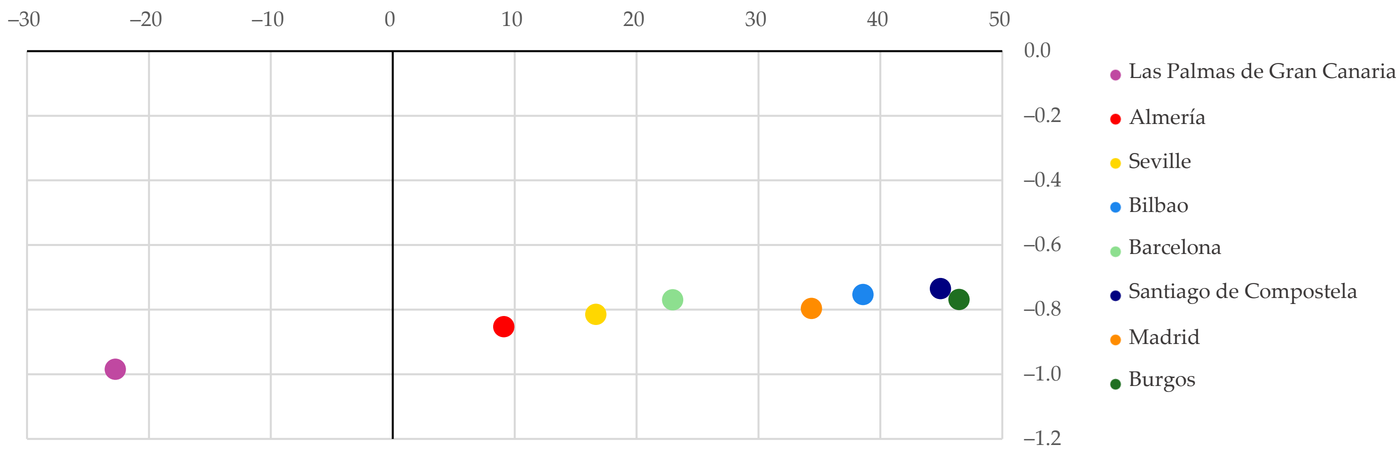

Figure 7. Total energy savings (%) of model B in relation to the reference model regarding heat losses by evapotranspiration (W/m^2) in each of the 8 cities.

This behaviour can be justified based on different concepts. In the first place, as they are self-sustaining green roofs, the water available for losses due to evapotranspiration is limited. Therefore, in areas with higher temperatures and solar radiation, greater heat losses are produced by evapotranspiration but are limited to the amount of water available, since these cities coincide with lower annual rainfall. These green roofs do not develop their maximum cooling potential by evapotranspiration.

On the other hand, regarding the geometry of the building, it is observed that the main orientations are south and west. These facades are the ones that receive the greatest amount of solar radiation and are also the ones with the highest proportion of openings (greater than 20%), while the north facade does not reach a proportion of 6% and the east party wall is adiabatic, in contact with the attached house. The proposed study only contemplates an improvement of the thermal envelope of the building, without the introduction of other elements of solar control. These elements could avoid the direct incidence of the sun and reduce the transmission of heat through the most exposed windows and facades. Therefore, the south and west facades, together with their windows, reach high outside temperatures throughout the day due to incident solar radiation. The increase in thermal insulation and inertia of the facades, at the same time as the solar control treatments of the window pane, reduce and delay the transmission of heat from the outside to the interior of the house. However, part of the heat will arrive, delayed in time, inside the rooms and will increase the indoor temperature. This heat cannot be dissipated naturally during periods when outdoor temperatures drop (such as, for example, at night) since the ventilation design is the minimum required by standards, air infiltrations from outside have been reduced thanks to the improvement of the construction and the high inertia of the envelope makes it difficult for heat to escape. In this case, there is an increase in cooling energy consumption, since it is the system used to reduce this indoor temperature.

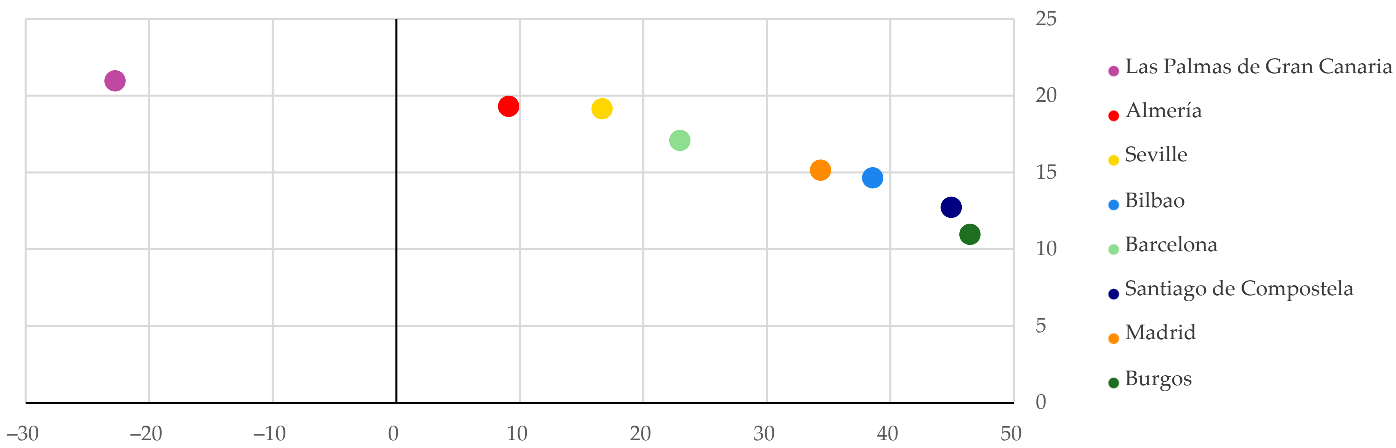

Figure 8. Total energy savings (%) of model B in relation to the reference model regarding the average annual temperature (°C) in each of the 8 cities.

In hot climates, with high direct solar radiation, these gains are very high and cooling consumption increases considerably from the consumption produced in the reference model without insulation, with less inertia and greater air infiltrations. In addition, in these cities, cooling consumption already accounted for a high percentage of total energy consumption (for example, in Seville, in the reference model, cooling energy consumption accounted for 22% of the total). With this circumstance that increases cooling consumption, the influence with respect to total energy consumption increases even more (41.7% in model B in Seville). On the other hand, in cold climates, where cooling energy consumption is minimal (for example, in Burgos, it is 1.2%) and heating energy consumption has a much greater weight (77.2%), in addition to being climates with less direct solar radiation, these gains are positive, since they heat the interior of the rooms and reduce the main energy consumption, that is, heating (49% in model B in Burgos).

4. Conclusions

The annual energy behaviour of a single family attached house type in eight Spanish cities has been analysed. These cities represent the six climatic zones and the five rainfall zones that exist in the country according to current standards. Starting from a house built before the first building standard about thermal insulation came into effect in Spain, the reference model is studied in each of the cities without insulating material and with a high value of air infiltrations. Subsequently, a renovation of the building is proposed, improving the entire thermal envelope and establishing three roof types: traditional with a gravel finish (model A), extensive self-sustaining green roof (model B) and intensive self-sustaining green roof (model C).

In the first place, it is observed that the total annual energy consumption reduces with the improvement of the thermal envelope in all the cities, except in Las Palmas de Gran Canaria (climatic zone α). This is due to the fact that it presents outdoor temperatures with fewer daily and annual variations, and is closer to the indoor comfort temperature.

Model B, due to the peculiarities of the substrate and the type of vegetation used in the extensive system, is the one that presents the more variable performance. While in most cities an increase in total annual energy consumption is obtained from model B regarding A, in Bilbao, Santiago de Compostela and Burgos savings are obtained with model B regarding A. To understand this phenomenon, the different climatic variables (temperature and solar radiation or rainfall) and their influence on the main mechanism of cooling and heat losses in green roofs (evapotranspiration) are analysed. It is observed that the greatest heat losses due to evapotranspiration are because of higher average annual outdoor temperatures and higher values of solar radiation. Annual rainfall does not seem to be decisive if it is not accompanied by high temperatures and solar radiation. In other words, despite being self-sustaining roofs and having a limited amount of water stored in the substrate and available for vegetation and evapotranspiration, cities in temperate and warm climatic zones with greater solar radiation present more evapotranspiration than those with moderate and cold temperatures, lower radiation and higher annual rainfall. For example, Almería or Seville present heat losses due to evapotranspiration of $-0.85\ \mathrm{W/m^2}$ and $-0.82\ \mathrm{W/m^2}$, while in Bilbao, Santiago de Compostela and Burgos, the lowest heat losses due to evapotranspiration are obtained, below $-0.80\ \mathrm{W/m^2}$.

Even so, it is observed that despite the fact that evapotranspiration is the main mechanism of heat dissipation on the surface of green roofs, greater losses due to evapotranspiration do not translate into greater energy savings in model B compared to the reference model. This is because, as they are non-irrigated roofs (self-sustaining), the amount of water available in the substrate and vegetation for evapotranspiration to occur is limited, especially in climates of dry and hot summers, so this phenomenon does not reach the desired magnitude. In this case, the outdoor temperature is more relevant, achieving greater energy savings in cities with colder climates and greater annual and daily temperature variations. In this case, the energy savings obtained in cities such as Bilbao, Santiago de Compostela, Burgos and Madrid are greater than 34%, while in cities such as Almería, Seville or Barcelona, the savings obtained are 9.1%, 16.7% and 23%, respectively. In addition to the limitation of evapotranspiration, the orientation and design of the main facades also influence these data. The increase in the thermal inertia of the envelope, while reducing air infiltrations, must be accompanied by adequate ventilation of the spaces that allow the heat accumulated indoors to be dissipated. Otherwise, as can be seen, the cooling energy consumption is increased, as it is the only mechanism available to reduce the indoor temperature. This increase is even more evident and harmful in hot climates, especially with high incident solar radiation.

A design of solar control elements that limit the incidence of direct solar radiation in the envelope, as well as the determination of minimum irrigation (compatible with the water stress problems) could improve the energy savings obtained through the use of green roofs, especially in dry and hot climates with high solar radiation.

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