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Irrigation proposals for improving the energy performance of green roofs in Mediterranean climate

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ABSTRACT

The evapotranspiration and cooling energy saving potential of green roofs is very great in the Mediterranean climate, due to high levels of solar radiation. However, the low rainfall limits these losses. The main goal of this research is to determine the energy savings achieved by increasing water availability by installing an irrigation system. It is proposed the computer simulation of a building renovated with three construction systems, according to real scaled models. Irrigation proposals are studied from two perspectives: (1) different irrigation rates for each green roof system and (2) different irrigation schedules. From the perspective of irrigation rates (1) it is observed that increased water input in extensive green roofs does not lead to increased evapotranspiration heat losses due to their limited water storage capacity. In extensive green roofs, increasing the water supply above the storage capacity implies increasing water outflow, but not heat losses. In relation to the irrigation schedules (2) the models with daily annual irrigation achieve very limited total savings, less than 1% compared to self-sustaining models. However, a daily irrigation system only during cooling periods achieves greater total savings, between 1% and 2% compared to self-sustaining models. The system is optimised by increasing energy savings and reducing water consumption. On green roofs in the Mediterranean climate, the increase in available water does not necessarily imply an increase in total energy savings. In these cases, it is essential to find a balance between limiting water consumption and reducing energy consumption.

1. Introduction

Green roofs have a very complex behaviour from all the points of view that are related to sustainability. In the economic field, the high construction cost and the greater maintenance of this type of roof [1–3] do not compensate, in an initial phase of the project and choice of the construction system, the energy benefits obtained [4] and the extension of the lifespan of the roof and its layers [5,6].

But these calculations omit highly relevant social and environmental aspects, since it is very difficult to account for these benefits [7]. As is the case of the upgrade of people's physical and psychological health, thanks to the proximity of natural spaces and the consequent improvement in air quality [8,9], the reduction of Urban Heat Island (UHI) due to the increase of pervious surfaces and/or with higher albedo [10,11], the increase of spaces to improve social contact and the stress reduction [12,13]. Some experiences, such as the green roof bidding in the city of Barcelona (Spain), demonstrate the great public awareness that can be accomplished by achieving sustainable goals through green roofs [14].

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Specifically, the UHI is a problem of great importance and its reduction, thanks to the increase of green spaces in the urban fabric, should be considered as a priority. The UHI occurs in urban centres due to the large number of existing hard, reflective and impervious surfaces, such as asphalt, which work as heat emitting sources [4]. The thermal behaviour of the city is modified, reaching up to 12 °C more in the central neighbourhoods than in the suburbs, which has more green areas [4]. But the UHI also occurs due to other factors, such as fewer green areas, with a reduction on shading and radiation interception, less airflow through urban canyons, and high heat production as waste from HVAC systems, vehicle traffic and industrial processes [10,15,16]. This phenomenon implies serious consequences for the environment, such as the generation of stress in aquatic ecosystems [17] or the increase in the use of refrigeration systems, a greater use of energy and, depending on the energy sources used, an increase in polluting gases. Therefore, there is an increase in the greenhouse effect, and, closing the cycle, an increase in the global temperature of the planet [17]. But it is also a serious problem for people's health, since UHI implies a greater mortality associated with heat strokes [18] and an increase in urban air pollution, since new airflows appear that pull the colder air from the suburbs to the centre of the cities, bringing with it the usual pollution from industries and highways located on the suburbs [19].

It is also important to assess other highly relevant environmental benefits in a society whose goals are aimed at fighting and mitigating the effects of climate change, such as the reduction of rainwater runoff [17,20], thus reducing the danger of floods, increasingly likely due to intensification of extreme weather events, thanks to the increase of pervious surfaces [21,22].

In this case, strategies should be considered that encourage the use of this type of sustainable construction solutions, either focusing on those social and environmental characteristics that will revert to all users of the city, and/or increasing the energy efficiency of these solutions, reducing the energy consumption associated with achieving thermal comfort conditions inside the building during its useful life. In particular, both the reduction in buildings energy consumption and in temperature close to the surface, thanks to the greater thermal inertia of the green roof system [23], heat losses through evapotranspiration [24] and the shadow projected by the vegetation [25], they allow to reduce the UHI, as mentioned in the previous lines, and the air-conditioning energy consumption. This improvement in the energy efficiency of buildings depends on the construction of the building itself. The thermal and energy contribution of the green roofs is lower in better insulated buildings. That is why green roofs are recommended, especially, in the renovations of buildings with poor thermal conditions and little insulation in the envelope, achieving greater energy savings in air-conditioning [26–29].

Green roofs, therefore, imply a wide range of benefits for city users and the environment. The commitment of public administrations to reduce climate change and improve the health of current societies, structured around sustainable goals (such as the Sustainable Development Goals of United Nations), must materialize in a greener and more resilient construction and architecture. Thus, public policies on promotion of green roofs are a very effective tool to encourage their use and make the environmental and social benefits of this type of vegetal systems prevail over a less favourable economic study compared to a traditional roof [30]. In this sense, cities such as Toronto (Canada), Portland (USA), Darmstadt (Germany), Basel (Switzerland) or Barcelona (Spain) among many others, introduce economic bonuses or tax reductions to help owners who install green roofs [5,14,23].

From the point of view of increasing the energy competitiveness of this type of roof, it is very important to carefully study the thermal conditions of the building and the climatic characteristics of the environment. In the case of the renovation of buildings with little or no previous insulation in the envelope, the energy savings achieved thanks to the improvement of roof construction system are very relevant. But the benefits that can be achieved with these renovations are, in turn, highly conditioned by the climatic environment, such as outdoor temperature, solar radiation and precipitations [31].

The increasing scarcity of water, due to climate change, increases the concern about water consumption, especially for non-human use [32]. In this context, self-sustaining green roofs, without an irrigation system, present advantages such as economic savings derived from the cost of the irrigation system and water consumption and the non-use of an increasingly scarce natural resource [33]. This type of roof only receives water derived from the different rain events, so its availability throughout the year will be limited, thus conditioning the growth and development of the vegetation and the phenomenon of evapotranspiration, with a consequent limitation in the energy savings achieved in air conditioning [33,34].

In locations with low rainfall and long periods of drought, the installation of an irrigation system on the green roof increases the availability of water, the heat losses due to evapotranspiration and the consequent lower external and internal surface temperature of the roof, especially in climates such as the Mediterranean (high solar radiation, moderate/high outdoor temperature and low rainfall) [26,35–37]. These benefits can mean a reduction in energy consumption, but also the improvement of other behaviours, such as UHI mitigation [38].

The main goal of this research is to determine the potential energy savings achieved by installing an irrigation system, compared to self-sustaining green roofs (without irrigation), in the Mediterranean climate.

But it is important to find a balance between water consumption and reducing energy consumption. One of the consequences of climate change is the increase in the difference between dry and wet areas and seasons [32]. In particular, Spain is currently one of the major European countries with the highest rate of water stress, especially on the Mediterranean coast areas [39,40]. In addition, cyclical droughts occur in Spain [39]. In these months or periods of drought or high degrees of scarcity, the use of water is cut back in those areas in which it does not directly affect human consumption, such as in the irrigation of urban green areas or gardens [32]. For this reason, it is necessary to establish a series of strategies that allow finding a balance between water scarcity and the renaturation of cities to mitigate the effects of climate change.

Based on the mentioned water resource use, the study of the energy improvement of a house through the introduction of an irrigation system is proposed, trying to improve the energy behaviour with respect to self-sustaining green roofs, in a Mediterranean climate. The most common irrigation systems are sprinkler and drip irrigation, the latter being the most suitable, since it prevents water losses through evaporation since it is a buried system, which is based on providing small amounts of water with high frequently, near the roots of the plant, so that the water is distributed by capillarity [5,41,42]. With the intention of further optimizing the irrigation, it is recommended to store and use rainwater or install a purification system to use the greywater produced by the building [41]. Greywater is between 65 and 90% of the water wasted by a house, usually originating from washing machines, sinks or the kitchen, so its use as irrigation water in green roofs allow to optimize resources and achieve a more sustainable design. In addition, the greywater that comes from the kitchen is rich in nutrients, so the use of fertilizers would be minimized [43].

In accordance with the main goal, the computer simulation of several models with different amount of irrigation water supply and frequencies is proposed, on two green roof systems (extensive and intensive). The evapotranspiration and/or energy savings obtained in each case are studied with the intention of determining which irrigation proposal is the most appropriate under the precept of water consumption-energy savings balance.

The study of different irrigation proposals is carried out from two different perspectives:

1) The appropriate irrigation rate for each green roof system (extensive and intensive) is determined based on its storage capacity.
2) Different irrigation schedules are considered, installing this system throughout the year or only in warm season or cooling period.

This double orientation will improve the balance between water consumption and energy savings obtained, carrying out the study based on computer simulations that allow simulating different cases of renovation of a single-family semi-detached house located in the city of Valencia (Spain).

2. Materials and methods

The case study in Valencia (Spain) is a 77.2 m^2 single-family semi-detached house, built between the 1950s and 1960s. It is before the first Spanish standard that introduced concepts of insulation in the envelope of the building came into effect in 1979 [44]. This building to be renovated will be called as "reference model" (Fig. 1). Therefore, it is a building without insulation in the envelope, on which the improvement of the roof construction system is proposed. In locations with high solar radiation, and high temperatures in hot seasons and moderate temperatures in cold seasons, the thermal improvement of the roof system represents energy savings, compared to the reference model, around or greater than 50% when compared with the energy savings obtained by thermally improving the entire building envelope (facades, windows, roof, slab on grade and party wall) [31]. In accordance with the climatic characteristics of Valencia, the renovation of only the roof is proposed, based on three construction systems: traditional roof with a gravel finish (model A), extensive green roof (model B) and intensive green roof (model C).

Both the reference model and models A, B and C are simulated throughout an entire natural year, considering temperatures, relative humidity, solar radiation and rainfall for the location of Valencia.

The reduction of energy savings achieved in air conditioning due to the scarce availability of water on the roof gardens is especially relevant in locations such as the city of Valencia (Spain). This is located in an area of Spanish territory with water scarcity and possible risk of desertification in the coming decades [39,40]. In addition, according to the Köppen classification [45], it is considered a Mediterranean climate with dry and hot summers (Csa). According to current Spanish standards [46], Valencia has an annual rainfall index between 300 mm and 500 mm. Therefore, rainfall is really scarce. Moreover, most rainfall occur in specific periods (months of March–May and October–November), generating long periods without rainy events, or of very little magnitude. Therefore, in the case of the green roof models (B and C), the computer simulation of different irrigation options is proposed to maximize the energy benefit of these roofs, while trying to regulate water consumption.

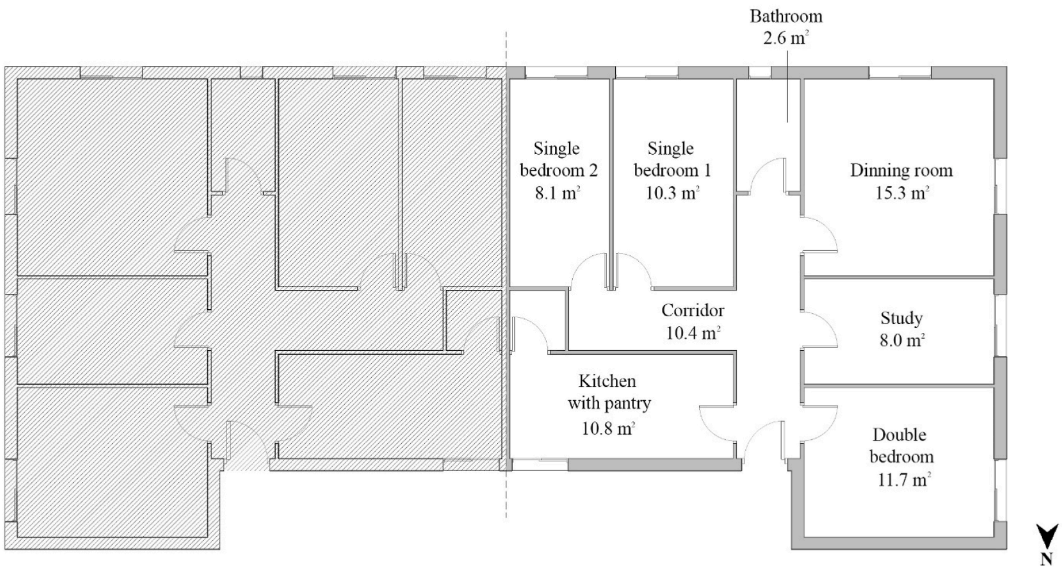

Fig. 1. Floor plan of the house case study: distribution of interior spaces and dimensions (m^2).

To carry out these simulations, the programs OpenStudio and EnergyPlus are used. The thermal behaviour of green roofs is very complex, especially in the finishing layers. Based on the simplified FASST model [47], Sailor [48] develops a system for calculating the heat transfer between the layers of vegetation and soil. This system is considered sufficiently accurate [49] and it is integrated into the EnergyPlus calculation engine.

2.1. Scaled models and real data

In order to verify and validate the generated computer models, three scaled models are built, with dimensions 1x1 m2. They are configured according to the distribution of layers of the three models A, B and C (Fig. 2). The green roof scaled models are self-sustaining. The dimensions respond to the necessity of creating small scale models, but in which the probes (located in the center of the models) are sufficiently protected and isolated, preventing the boundary conditions from negatively affecting the data collection. These scaled models are located at the Universitat Politècnica de València (UPV), in a space set up by the Infrastructure Service, for a full year in which humidity and temperature data are collected between the different layers that make up the systems.

The choice of these models (A, B and C) responds to the conclusions drawn from a previous study of 17 roof models (16 green roofs and 1 reference model, without vegetation, with a gravel finish) [50,51]. The main variables that influence the choice of a suitable construction system in the field of building renovation have been analyzed: construction cost, self-weight and compliance with current energy standards. The three models A, B and C have a roof transmittance of less than 0.33 W/m^{2}K, the recommended limit value in current Spanish standards, in relation to energy consumption and energy savings in buildings [52]. This value depends on the climatic zone in which the building is located, being 0.33 W/m^{2}K for the climatic zone of Valencia.

Model A, with a gravel finish, has been chosen as an example of a current non-sustainable construction system, predominant in a large amount of buildings. In the case of model B, extensive green roof, due to the low construction cost and self-weight, presumably supportable by a building built in Spain in the aforementioned decades (1950–1960), it is considered the most appropriate option for a case of refurbishment. It is intended to compare its energetic behaviour with model A, widely used but not green. Regarding model C, intensive green roof, it presents excessive construction costs and self-weight, and is not very suitable for renovation. In this case, the choice of this model is focused on the comparative energy study with model B, similar, but with less thickness of the soil layer. A similar energy behaviour of both models would confirm that model B is the most suitable for the case of energy renovation of a building, not only because of its low self-weight and construction cost, but also because of its adequate thermal and energy behaviour.

For each of the scaled models, a wooden box is built with the respective layer distribution, arranging between them probes connected to the TH1165 data-loggers, from the Perfect Prime brand [53]. The data-loggers work autonomously (Battery: 3V, AAA x2) and each record includes the values of temperature, dew point, relative humidity, date, time and number/name of the probe. The measurement range of the data-logger, with probe, is between −40 °C and 125 °C, with an accuracy of ± 0.3 °C @ 25 °C. Regarding relative humidity, the measurement range is between 0% and 100%, with an accuracy of ± 2% @ 25 °C.

One of the main problems of this type of data-loggers is the fast battery consumption and the limited data storage capacity (21,000 records, maximum). For them, a recording frequency of 30 min is determined, looking for a balance between battery consumption, the data storage capacity and the need for continuous data recording to properly reflect the temperature and relative humidity trajectory. This interval is considered sufficient, providing a good performance of the data-logger and considering the data obtained as conclusive [54]. The collecting data is done every 7–14 days during the 12 months that the study lasts. Table 1 shows the amount of data recorded by each of the probes, in each model. In addition, the total number of data recorded by all probes in all models throughout the study year is collected: 235,765 records.

The climatic data (outdoor temperature, relative humidity and rainfall) are obtained every 10 min, from the station of the Agencia Estatal de Meteorología (AEMET, Spanish State Meteorological Agency) located at the UPV. Regarding solar radiation data, they are obtained every hour from the AEMET station located at the Valencia airport.

The distribution of layers and the location of probes is described in Fig. 3. For the execution of the scaled models, the trading house ZinCo Cubiertas Ecológicas S.L. collaborated with the supply of part of the material [55]. The nomenclature and properties of the different layers are those specified by the trading house, indicating below the specific name of the layers supplied.

In the case of model A, with a gravel finish, there are (from bottom to top): 0.1 cm thick EPDM waterproof sheet, separation membrane TGV 21, 8 cm thick XPS thermal insulator, separation membrane TGV 21 and a layer of gravel 6 cm thick, light-coloured

(A) (B) (C)

Fig. 2. Scaled model of roofs, at the time of installation (February 25, 2021): (A) traditional with gravel finish; (B) green extensive; (C) green intensive. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Records of temperature and relative humidity: by probe, model and in total during the year of operation.

Probes	Model A	Model B	Model C	Total records
P_1	18,638	18,117	18,742	55,497
P_2	18,259	18,753	14,588	51,600
P_3	18,556	16,893	18,489	53,938
P_4	18,970	18,367	18,569	55,906
P_5	-	-	18,824	18,824
Total records	74,423	72,130	89,212	**235,765**

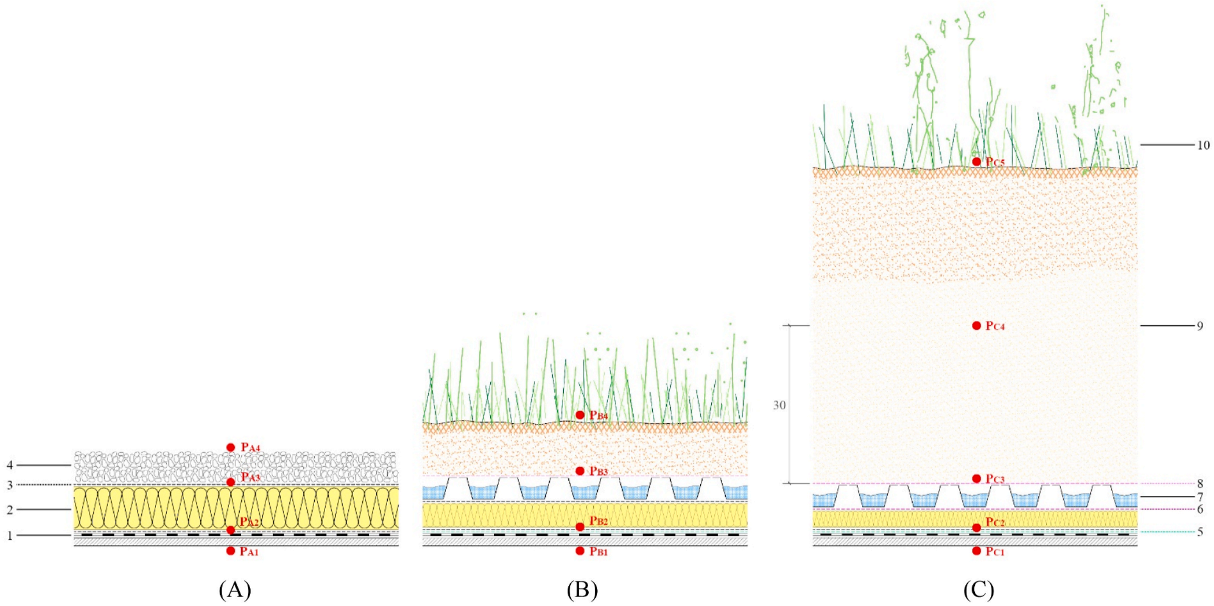

Fig. 3. Roof scaled models and probes location: (A) traditional with gravel finish; (B) green extensive; (C) green intensive. Legend: (1) EPDM waterproof sheet; (2) XPS thermal insulator; (3) Separation membrane; (4) Gravel; (5) Root barrier; (6) Protection mat (water storage); (7) Drainage layer; (8) Filter sheet; (9) Soil; (10) Vegetation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

rounded edges and Ø 2–4 cm. In this case, there are four probes (P_{A1}-P_{A2}-P_{A3}-P_{A4}). It should be noted that the scaled model rests on a base made up of two boards of insulating material, with the P_{A1} probe between them and more protected from the outside.

The distribution of model B is: 0.1 cm thick EPDM waterproof sheet, root barrier WSF 40, separation membrane TGV 21, 5 cm thick XPS thermal insulator, separation membrane TGV 21, drainage layer Floradrain FD 40-E, filter sheet SF, System Substrate "Rockery Type Plants" 10 cm thick and succulent vegetation (*sedum album*, *spurium* and *spurium* type *conccineum*). Four probes (P_{B1}-P_{B2}-P_{B3}-P_{B4}) are arranged. For model C, the layers are as follows: 0.1 cm thick EPDM waterproof sheet, root barrier WSF 40, separation membrane TGV 21, 4 cm thick XPS thermal insulator, protection mat SSM 45, drainage layer Floradrain FD 40-E, filter sheet SF, System Substrate "Roof Garden" 60 cm thick and aromatic subshrub vegetation (*armeria maritima*, *santolina chamaecyparissus* and *thymus vulgaris*). Five probes (P_{C1}-P_{C2}-P_{C3}-P_{C4}-P_{C5}) are arranged.

2.2. Computer models for simulation

In relation to the simulated models, Table 2 identifies the main characteristics of the finishing materials of the roof systems A, B and C. The data needed for the vegetation layer is not easy to obtain. Therefore, a bibliographical review of investigations that have modelled, especially with EnergyPlus, green roofs whose vegetation characteristics resemble those used in this study, is carried out. The information exposed regarding the vegetation has been taken from the investigation carried out by Ascione et al. [56]. In relation to the soil, the necessary data has been obtained from the technical data sheet of the product used in the scaled models (System Substrate "Rockery Type Plants" and "Roof Garden") and previous investigations that provide proven and reliable values [33,57].

In all three cases, a renovation of only the roof is proposed, going from an initial thermal transmittance of the reference model (U_R) of 1.177 W/m^{2}K. After the renovation, the thermal transmittance values are 0.307 W/m^{2}K in model A (with a thickness of thermal insulator of 8 cm), 0.317 W/m^{2}K in model B (with a thickness of thermal insulator of 6.5 cm) and 0.306 W/m^{2}K in model C (with a thickness of thermal insulator of 3 cm). In the three cases of renovation, it is established as a premise that the thermal transmittance is less than or equal to 0.33 W/m^{2}K. In no case is a green roof designed without a layer of thermal insulator, since despite complying with the thermal transmittance calculation only with the thickness of the soil layer, the variation in its moisture content produces changes in its thermal conductivity and derived problems [42]. Therefore, in all cases the provision of a minimum layer of 3 cm of thermal insulator is considered.

Table 2
Main characteristics of the finishing materials chosen for the models simulated for the roof renovation.

	Model A	Model B		Model C	
Characteristics of the finishing materials	Gravel	Soil	Vegetation: Succulent	Soil	Vegetation: Subshrub
Thickness (m)	0.060	0.10		0.60	
Conductivity (W/mK)	2.00	0.435[a]		0.435[a]	
Density (kg/m^3)	2200.00	940.00[a]		940.00[a]	
Specific heat (J/kgK)	800.00	1420.00[a]		1420.00[a]	
Solar reflectivity (Albedo)	0.30	0.10		0.10	
Height of plants (m)			0.10		0.40
Leaf Area Index (LAI)			0.10		2.00
Leaf reflectivity			0.25		0.20
Leaf emissivity			0.95		0.95
Min. stomatal resistance (s/m)			300.00		120.00

[a] Values are expressed for dry soil.

It should be noted that in the case of the scaled models there are differences in the thickness of the thermal insulator of models B and C. In the case of model C, a thickness of 4 cm is used in the scaled model, since the trading house that has supplied this product does not market XPS boards of lesser thickness. Regarding model B, in the initial calculations of thermal transmittance of the roof, prior to the computer energy simulations and the construction of the scaled models, a simplified value of thermal transmittance of the soil and vegetation layers was chosen [58]. Due to the great complexity of the heat transfer phenomena in these layers, this simplification, whose calculation indicated that a 5 cm layer of thermal insulator was necessary, turned out not to be accurate enough [33]. Once the calculation was made using the EnergyPlus and OpenStudio programs, whose analysis of the thermal behaviour of the soil and vegetation layers is more detailed, a 6.5 cm thick layer of thermal insulator was established as necessary. These differences, however, do not pose a problem since the values that are compared between scaled models and computer simulations are the outside surface temperatures of the roof, in which the different thickness of the insulating layer does not imply changes.

Regarding the air conditioning systems, the heating setpoint temperature is established at 21 °C and the cooling one at 25 °C.

The main objective of the research is to determine the energy savings obtained by increasing the available moisture content in green roofs, compared to a self-sustaining one (without irrigation). For this, the simulation of different drip irrigation hypotheses is proposed, based on two perspectives. (1) The balance between water consumption and energy savings is addressed from the irrigation rate. Both green roof models (B and C) have different water storage capacities. Therefore, in section 3.2, its individual behaviour with three irrigation rates is studied with the intention of determining which is the most appropriate for each model (minimizing water consumption and maximizing benefits).

(2) The water-savings balance is considered by studying different frequencies of water supply (schedules). Three irrigation annual schedules are proposed, in section 3.3, studying their effect on the annual energy savings obtained. The case without irrigation is valued, the case of daily and constant irrigation throughout the year and, finally, daily irrigation only during the cooling period. In the two cases with irrigation, the drip irrigation is programmed daily from 04:00 h to 05:00 h, avoiding water losses by evaporation, derived from incident solar radiation.

3. Results and discussion

3.1. Real data and computer models validation

From the data obtained in the scaled models of self-sustaining green roofs, it is perceived that the low availability of water, especially in times of low rainfall, produces a limitation of heat losses through evapotranspiration. The detailed study of a period with different moisture content in the green roofs allows to analyse the clear influence of this variable on the thermal, and therefore, energy behaviour of the green roofs. The days from January 20 to 29, 2022, include the last three days of a drought period (from 20 to 22), a period with rainfall (from 23 to 25, with 0.6, 1.5 and 6.2 mm rainfall, respectively) and the following days, with a higher stored water content (from 26 to 29).

Fig. 5 shows how in model B, the day after the rainfall, January 26, the relative humidity detected in probe P_{B4} is, both in its maximum and minimum values, higher than in the days before the rainfall. This means that more evaporation of the soil happens. It translates into a maximum surface temperature the same day up to 2 °C below the surface temperature of the days before the rainfall. This occurs despite the fact that both solar radiation and outdoor temperature are higher on day 26 than on days 20–22 (Fig. 4). Due to the lower water storage capacity of the extensive green roof, the humidity values decrease on the surface of the soil from day 27, increasing the surface temperature. In the case of model C, a very similar behaviour is detected, but evaporation decreases from day 28, then remaining constant, thanks to the greater water storage capacity. This implies higher surface temperatures from this day on.

In other words, self-sustaining green roofs could increase their heat losses through evapotranspiration by increasing the availability of water (in each type of green roof adapted to its storage capacity). Since, as shown in Fig. 5, an increase in water content means greater losses and lower surface temperatures. In this case, the study, through computer simulations, of various irrigation hypotheses on these scaled models is considered necessary, with the intention of increasing their energy savings.

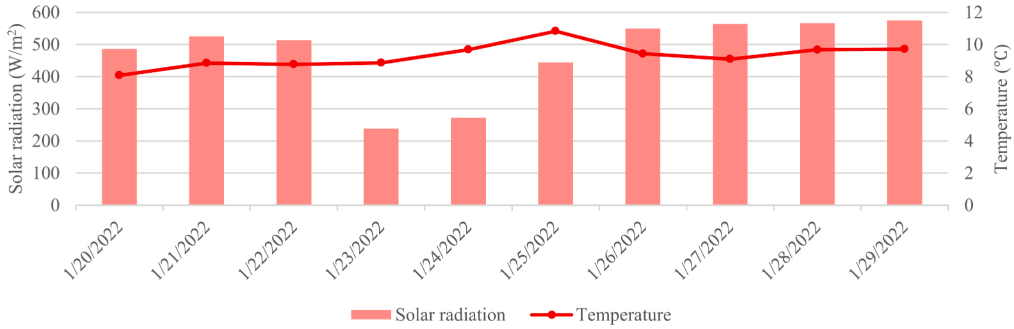

Fig. 4. Maximum daily solar radiation (W/m^2) and average daily outdoor temperature (°C) between January 20 and 29, 2022.

For this, it is necessary, first of all, to validate the computer models, ensuring their reliability and reproduction of the same models that have been built. For validation, the same period previously studied is chosen, from January 20 to 27–29, 2022. Considering the variation of the thermal behaviour of the soil and vegetation depending on the stored water, it has been considered relevant to simulate a period of greater complexity by presenting days with a dry soil and little water availability and days with wetter soil after the rain. In this period, it is compared the data recorded in the surface probes of the scaled models (P_{A4}-P_{B4}-P_{C5}) with the simulated outside surface temperatures. In the case of models A and C, it is studied from the 20th to the 29th, while in model B, due to a probe failure on the 27th at 22:00 h, only the data from January 20 to 27 are compared (Fig. 6).

The root-mean-square error (RMSE) obtained by comparing the real and experimental values of outside surface temperature is 2.7, 1.7 and 2.6 for models A, B and C, respectively. These values are in line with the results obtained by other authors [37,48,49].

3.2. Irrigation rates

Three irrigation rates are proposed, according to the consulted bibliography [37]: (i_1) 0 mm; (i_2) 3 mm; (i_3) 6 mm. The two rates i_2 (3 mm) and i_3 (6 mm) are simulated in both the extensive (B) and intensive (C) green roof models, with the intention of assessing which of the two is the most appropriate for each situation. To do this, the increase in heat losses due to evapotranspiration in i_2 and i_3 is studied, in comparison with the heat losses due to evapotranspiration that occur in the vegetation layer and soil in the assumption without irrigation (i_1). The daily evolution is analyzed on a representative day of the cooling period (July 12).

In the case of model B (Fig. 7) it can be observe how the greatest heat losses due to evaporation in the soil occur in the irrigation rate i_2, while the losses due to evapotranspiration in the vegetation layer are practically the same in both irrigation rates i_2 and i_3. The greater intensity of irrigation i_3 does not imply greater losses by evaporation in the soil, probably due to the low storage capacity of this layer, 0.10 m thick. In the case of vegetation, the ability of sedum-type succulent vegetation to regulate the opening of stomata at times of intense solar radiation, high outdoor temperatures, and low water availability (due to the limited storage capacity of the soil) explains that the heat losses in both irrigation intensities (i_2 and i_3) are very similar. In this case, a greater daily contribution of water does not imply greater heat losses, although it does imply a greater consumption of water and economic cost, therefore, the irrigation rates to be installed in model B will be: (i_1) 0 mm; (i_2) 3 mm.

In the case of the intensive green roof model (C), the greater thickness of the soil layer (0.60 m) allows to store a greater amount of water. Therefore, a greater availability of water produces an increase in the evaporation heat losses in the soil throughout the whole day with irrigation rate i_3. As the irrigation is programmed during the early morning, it can be observed how the model with irrigation rate i_2 presents evaporation values of the soil similar to the model with i_3 during the initial hours of the day (Fig. 8). But at 12:00 h there is a drop in heat losses in the soil of the model with i_2, which can be justified by the lack of water, due to the intense losses by evaporation in the first hours and the lower intensity of irrigation. Both in the case of the soil and vegetation, a considerable difference is noted between the model without irrigation (i_1) and the models with some irrigation intensity. Regarding heat losses due to evapotranspiration in the vegetation layer, they also increase with higher irrigation intensity. In this case, the subshrub type vegetation is not capable of regulating the opening of the stomata and minimizing evapotranspiration and water consumption in times of water stress, so the different irrigation intensity visibly affects the heat losses produced, unlike model B. The irrigation rates to be installed in model C will be: (i_1) 0 mm; (i_3) 6 mm.

3.3. Irrigation schedules and energetic behaviour

According to the conclusions drawn, models A, B and C are simulated considering: (A-B-C) only rainfall and no irrigation, i_1; (B1-C1) daily irrigation throughout the year with i_2 for the extensive model and i_3 for the intensive model; (B2-C2) daily irrigation from June to September (months with predominance in the use of cooling in the reference model) with i_2 for model B and i_3 for model C, while in the months of January to May and October to December, the irrigation system is not in operation (i_1). The annual energy consumption obtained in each case is shown in Fig. 9.

In the first place, a decrease in annual energy consumption can be observed, both for cooling, heating and total consumption (cooling, heating, lighting and electric equipment), by renovating and improving the roof construction system. The installation of a green roof system, both extensive (B) and intensive (C), produces greater savings compared to the reference building, without insula-

Fig. 5. Dot plot with relative humidity (%) and temperature (°C) data from probes P_{B4} (upper) and P_{C5} (lower) between January 20 and 29, 2022.

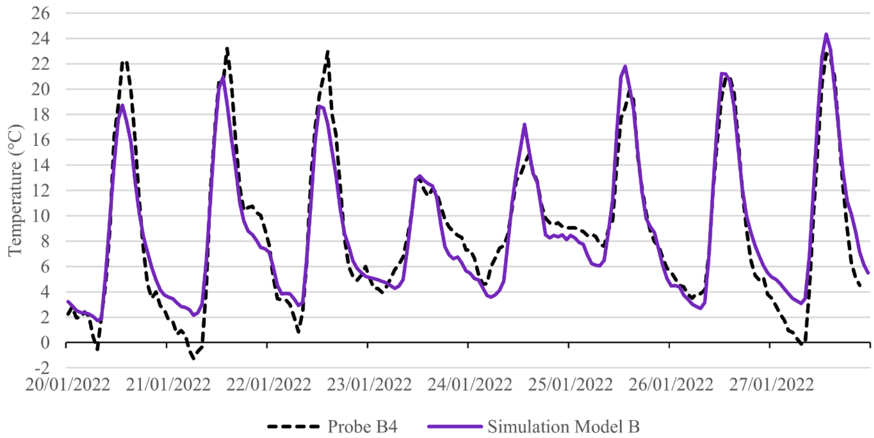

Fig. 6. Outside surface temperature of the scaled model (Probe B4) and the simulated model (Simulation Model B) between January 20 and 27, 2022.

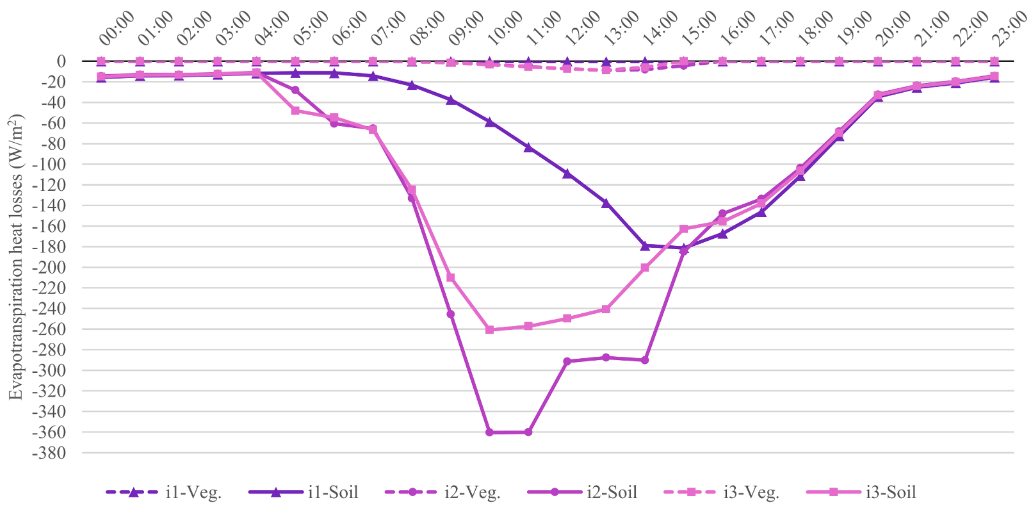

Fig. 7. Evapotranspiration heat losses in the vegetation and soil layers of model B for the three irrigation rates.

tion in the envelope, than compared to the savings obtained regarding the model A, with a traditional roof, but with sufficient insulation to comply with the limit transmittance of the standards in effect. The greatest savings in total annual energy consumption achieved with respect to model A occur in cases where irrigation is installed only during the cooling period (B2 and C2) with savings of 0.84% and 1.88%, respectively. These data agree with the values and reflections of Berardi [59], concluding that the greatest savings were related to a greater thickness of soil and LAI of the vegetation.

In the green roof models without irrigation (i_1) the availability of water is conditioned by rainfall, which is not very abundant on the Spanish Mediterranean coast and is mainly grouped in the spring and autumn months. Therefore, during the cooling period (June to September), with high outdoor temperatures and intense solar radiation, the rains are more scattered and less intense. This produces less water availability for the soil and vegetation, limiting evapotranspiration heat losses. Therefore, the annual cooling consumption of models B and C is lower than the cooling consumption of the reference model, but higher than the consumption of model A (Table 3). The savings obtained in cooling in the green roof models regarding the reference model are between 21% and 37%, data that agrees with the investigations of Santamouris et al. [60].

For this reason, the installation of a daily irrigation system (B1 and C1) is proposed, with the intention of increasing the availability of water and the dissipation of heat on the surface of the green roof, especially in times of high outdoor temperature and solar radiation [61,62]. In the city of Valencia, the annual cooling consumption supposes, in the reference model, a 18.53% of the total consumption. This value is relevant and can be decreased by increasing heat losses through evapotranspiration. In the case of roofs B1 and C1, the annual cooling consumption is lower, reaching savings compared to the reference model of 5.33% and 9.01% higher than in the green roof models without irrigation (B and C). Instead, an increase in annual heating consumption is observed.

Especially the high solar radiation (Fig. 10), which can generate a thermal load on the roof 2 times greater than on a south-facing facade (in the northern hemisphere) [63], produces, throughout the year, an elevated outside surface temperature even in the months

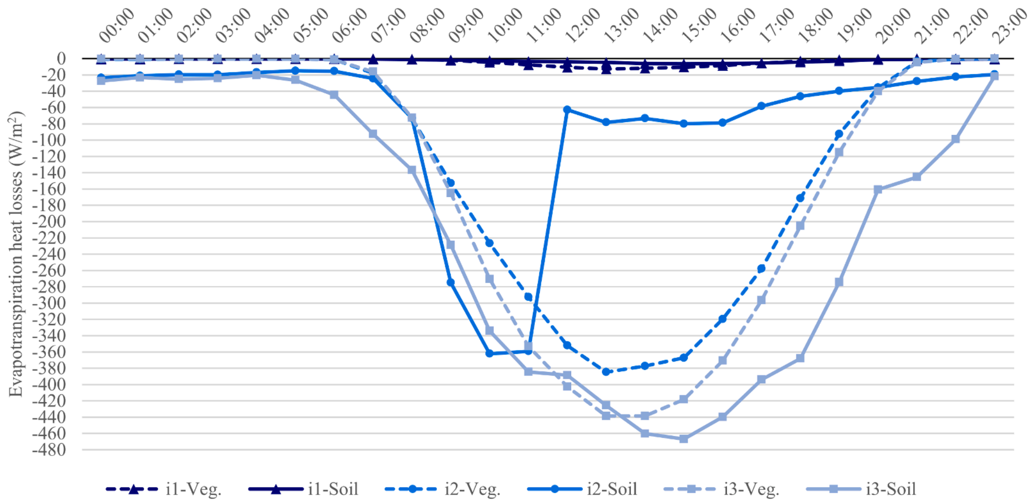

Fig. 8. Evapotranspiration heat losses in the vegetation and soil layers of model C for the three irrigation rates.

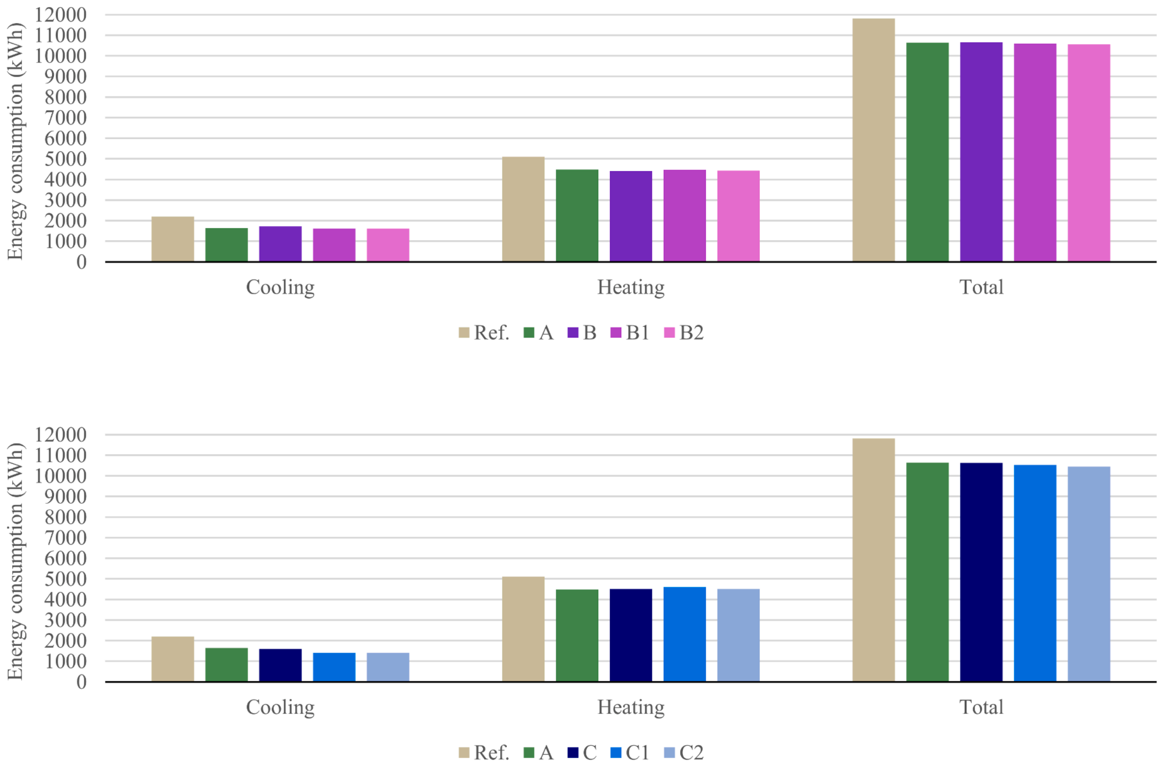

Fig. 9. Total and air conditioning systems annual energy consumption for the models: (Ref.) reference; (A) traditional with gravel finish; (B-B2) green extensive without irrigation during the heating period; (B1) green extensive with irrigation during the heating period; (C-C2) green intensive without irrigation during the heating period; (C1) green intensive with irrigation during the heating period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of predominance of heating with a lower or moderate outdoor temperature. In this case, an increase in the outside surface temperature in the renovated roofs also implies maintaining the highest interior surface temperature, and thus reducing the energy consumption of heating. At the same time, the reduction in the thermal transmittance of the roof ensures a decrease in negative heat flows, which cause the loss of heat produced inside, thus reducing heating consumption in all cases compared to the reference model.

As previously mentioned, and according to other investigations [61], solar radiation has a direct relationship and influence on the evapotranspiration that happens in the green roof, and therefore on the derived heat losses. An increase in the water stored in the soil,

Table 3
Energy savings (%) compared to the reference model in the different simulated renovation models.

Simulated renovation models[a]	Cooling	Heating	Total
A	24.75	12.36	9.92
B	21.19	13.50	9.76
C	27.03	11.65	10.04
B1	26.52	12.41	10.28
C1	36.04	9.69	10.87
B2	26.27	13.45	10.68
C2	35.66	11.59	11.62

[a] **A**: model A only rainfall and no irrigation/**B**: model B only rainfall and no irrigation/**C**: model C only rainfall and no irrigation/**B1**: model B with daily irrigation throughout the year, irrigation rate i_2/**C1**: model C with daily irrigation throughout the year, irrigation rate i_3/**B2**: model B with daily irrigation from June to September, irrigation rate i_2/**C2**: model C with daily irrigation from June to September, irrigation rate i_3

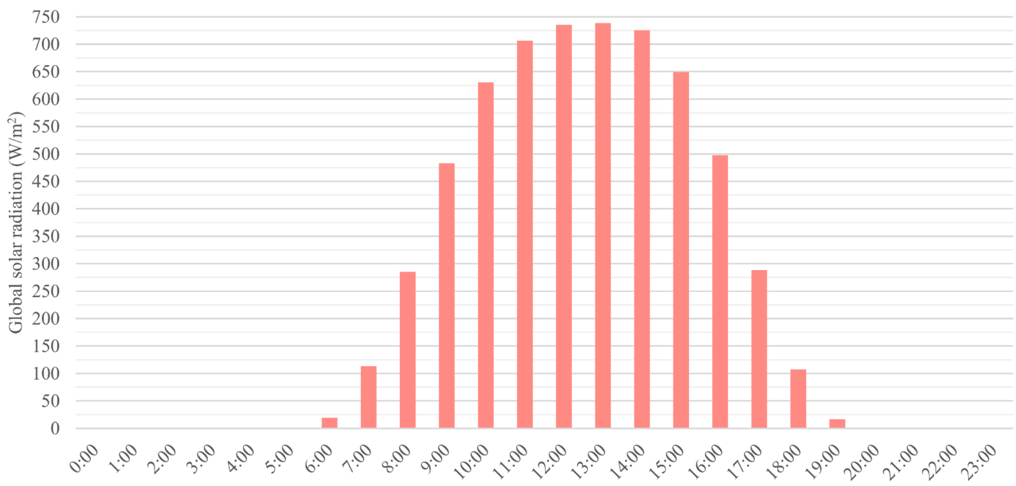

Fig. 10. Hourly annual mean global solar radiation (W/m2) of Valencia (Spain).

available for transpiration and evaporation of the vegetation, as well as for evaporation in the soil, will imply greater losses in the central hours of the day with a greater incidence of solar radiation. The increase in heat losses by evapotranspiration due to the high incidence of solar radiation and the greater availability of water (due to the installation of an annual daily irrigation), added to the shade provided by the vegetation, imply lower surface temperatures on the roof, which can be below outdoor temperature. This phenomenon, positive in warm seasons with a predominance in the use of cooling systems to reach comfort temperatures inside the building, is negative in periods with cold or moderate outdoor temperatures, with a predominance in the use of heating systems. In this context, a lower surface temperature means an increase in the consumption of indoor heating systems.

As can be seen in Fig. 11, the highest outside surface temperature on a representative day of the heating period (February 12) occurs in model A, reaching 34.95 °C. The outdoor temperature that day ranges from a minimum of 0.42 °C to a maximum of 16.00 °C. The extensive green roof models without irrigation throughout the year (B) or without irrigation during the heating period (B2) present a surface temperature very similar to model A, above 34 °C. This explains why models A, B and B2 are the ones with the greatest savings in heating compared to the reference model. On the other hand, the installation of a daily irrigation system during this period implies a lower outside surface temperature, with the surface temperature of B1 being 6.86 °C lower than the one of B and B2. The same occurs in model C. The greater depth of the soil and LAI of the vegetation imply lower outside surface temperatures, even in the models without irrigation during the heating period (C and C1), reaching maximums of 27.67 °C. In the case of installing irrigation during this period (C2), the drop in surface temperature is 12.98 °C compared to C and C1. The outside surface temperature reached by the C2 is 14.69 °C, a value even below the maximum outdoor temperature on that day.

It is important to avoid that, in times of predominance of heating consumption, the outside surface of the roof is too cold, with values that can be below outdoor temperature. Despite this, it should be noted that during the night and early morning hours the soil and the vegetation layer favour an increase in outside surface temperatures, compared to the surface of model A without greening, with values similar to those of the outdoor temperature.

In locations with high solar radiation, even in the cold months with lower temperatures (Fig. 10), the installation of an annual daily irrigation system does not imply substantial benefits, since the reductions in cooling consumption are offset by an increase in heating consumption. In this case the total annual savings regarding the reference model are very similar to models without irrigation, with differences of less than 1%. In this case, installing the irrigation system only during the cooling period, in addition to con-

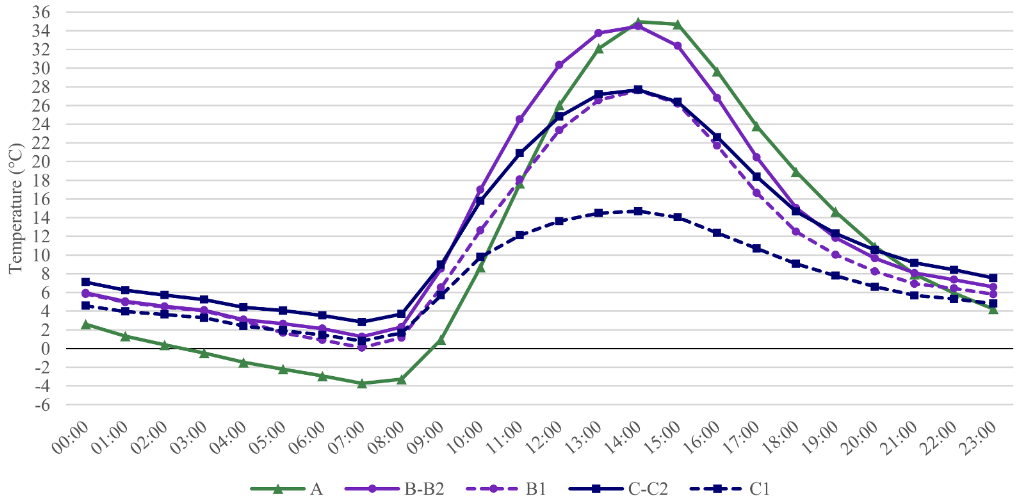

Fig. 11. Roof surface temperature for each simulated renovation model.

tributing to lower water consumption, reduces cooling energy consumption while reducing or not increasing heating consumption. The lower availability of water in the months when heating consumption predominates reduces heat losses on the roof surface, as well as reduces the thermal conductivity of the soil, as it is dry and with less stored water. In this case, the annual savings obtained are the highest of all the models studied. B2 and C2 represent a total annual energy saving of 1.02% and 1.75% compared to the models without irrigation (B and C), respectively.

When comparing models B2 and C2, it can be seen that the total annual savings obtained regarding the reference model differ by approximately 1%. Based on the self-weight of the system and the construction cost (variables of great importance in the field of renovation), the self-sustaining extensive green roof model is shown to be the best renovation system, obtaining total annual energy savings very similar to the intensive green roof, with higher cost and self-weight [31]. In this case without irrigation, the difference between the total savings obtained between models B and C regarding the reference model is even narrower (0.28%), due to the limited heat losses due to evapotranspiration. By the problem of water scarcity and the search for a balance between water and energy consumption, the model B2 model presents an energy behaviour very similar to that of the model C2, but with 50% less water consumption. This, added to its lower self-weight and construction cost, once again places the extensive model as the most appropriate construction system when considering the entire spectrum of variables.

4. Conclusions

The evapotranspiration potential of a green roof, and therefore its behaviour as a cooling element for the surface of the roof itself and the surrounding air, depends on different factors. From the point of view of the climatic environment, the high temperatures and values of solar radiation encourage greater heat loss through evapotranspiration. Valencia (Spain) enjoys more than 300 sunny days per year, with a maximum annual mean global solar radiation of over 700 W/m^2.

But evapotranspiration will be limited to the water content stored in the roof and, therefore, can be used in the evaporation of the soil and evaporation and transpiration of the vegetation to dissipate heat on the surface of the roof.

In this case, the scarce and irregular rainfall typical of the Mediterranean climate, specifically in Valencia, implies limitations in the heat losses of the self-sustaining green roofs, by limiting the amount of water available for evapotranspiration. The real data obtained from the monitoring of three roof scaled models (A: traditional roof with a gravel finish; B: extensive green roof; C: intensive green roof) allow to observe this limitation in the mechanisms of evapotranspiration in roofs without irrigation in Valencia. But it is also observed how the relative humidity values over the soil increase after a rainy period, with sufficient availability of water. Surface temperatures up to 2 °C below the values of the days before the rainfall, belonging to a dry period, are achieved despite the fact that the outdoor temperature and solar radiation are higher after the rainfall than the previous days.

Therefore, an increase in stored water in this type of climate, with high temperatures in summer, moderate in winter and high solar radiation all year round, presents a high cooling potential and a decrease in cooling and total energy consumption. Therefore, the installation of a drip irrigation system is proposed to improve the availability of water and the energy behaviour of self-sustaining roofs.

But the problems of desertification and water scarcity, notable on the Spanish Mediterranean coast, as well as in other areas, imply a necessary search for a balance between energy savings and moderate water consumption.

A study is proposed, through validated computer models, of a single-family semi-detached house renovated with three construction systems, according to the three scaled models. Irrigation proposals are studied from two perspectives: (1) different irrigation rates for each green roof system and (2) different irrigation schedules.

Regarding the (1) different irrigation rates, the intensive green roof model, with the highest water storage capacity (protection mat and 60 cm soil), presents the highest heat losses due to evapotranspiration in the soil and vegetation with the maximum irrigation rate proposed: 6 mm. However, the extensive green roof model does not increase losses by incrementing the irrigation rate from 3 mm to 6 mm.

In relation to the (2) different irrigation schedules, the installation of an annual daily irrigation system produces savings in cooling consumption of 26.52% for the renovation model with an extensive green roof and 36.04% for the intensive green roof, compared to the reference model. These values are 1.77% and 11.29% higher than the savings of model A, and 5.33% and 9.01% higher than the values of the green roof models without irrigation, B and C. But the high solar radiation even with lower outdoor temperatures, produces high heat losses through evapotranspiration and a surface temperature of the green roof that can even remain below the outdoor temperature. In this cooling period, this produces an increase in heating consumption, thus limiting the total savings obtained. In this case, green roof models with annual daily irrigation increase heating consumption by 1.26% and 2.22% compared to their respective self-sustaining models.

Some erroneous schedules can imply a decrease in the annual cooling consumption, but an increase in the heating consumption. The design of a daily irrigation system only during the months of predominance of cooling consumption (June to September), maintaining an irrigation rate of 0 mm (i_1) the rest of the year, ensures greater heat losses due to evapotranspiration in the cooling period. But contrary to a schedule with daily annual irrigation, the limited water content in the months when heating consumption predominates, depending only on rainfall, implies that the savings obtained in annual heating consumption compared to the reference model do not increase, or even decrease, in comparison with the savings achieved by self-sustaining models. Thus, green roof models with daily irrigation only from June to September achieve the highest total annual savings regarding the reference model among all the simulated situations. So, the system is optimised by increasing energy savings and reducing water consumption.

The following conclusions can be drawn from the two perspectives studied:

1) In extensive green roofs, increasing the water supply above the storage capacity implies increasing water outflow, but not heat losses.
2) In the Mediterranean climate, with high solar radiation all year round, the increase in available water does not necessarily imply an increase in total energy savings.

In both cases, it is confirmed the importance to find a balance between limiting water consumption and reducing energy consumption.

It should be noted that, during the spring and autumn months, especially from March to May and from October to November, the rainfall is usually more abundant, so that the vegetation has sufficient water availability for its survival and evapotranspiration phenomena. From November to February, the rainfall tends to be scarcer and more distant in time, a behaviour similar to summer months (June to September). Future research should focus on the study of the water needs of the installed vegetation to provide a minimum supply of water for its survival during these cold months. The scarcity of water and the increase in heating consumption should encourage the use of vegetation with low water consumption, adapted to the climate and capable of withstanding long periods without water (drought).

It follows from the study that the extensive green roof stands out even more as the most suitable constructive model for renovation, as it presents lower construction cost, self-weight, water consumption, water needs of the vegetation, while the total annual energy savings are very similar to the intensive green roof model due to limited water availability/consumption (differences around 1%). In a period like the current one, with an unstable increase in the energy cost, as well as urgent action against climate change, sustainable solutions that achieve certain energy savings must be considered and applied.

Credit author statement

Júlia G. Borràs: Methodology, Investigation, Resources, Writing – Original Draft, Writing – Review & Editing; **Carlos Lerma:** Term, Methodology, Writing – Review & Editing, Supervision; **Ángeles Mas:** Conceptualization, Methodology, Supervision; **Jose Vercher:** Conceptualization, Visualization; **Enrique Gil:** Software, Validation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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