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Environmentally Sustainable Green Roof Design for Energy Demand Reduction

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Abstract: Green roofs are artificial ecosystems that provide a nature-based solution to environmental problems such as climate change and the urban heat island effect by absorbing solar radiation and helping to alleviate urban environmental, economic, and social problems. Green roofs offer many benefits in terms of heat and water conservation as well as in terms of energy costs. This work proposes the design of an extensive and environmentally sustainable green roof for the Faculty of Engineering building in Bilbao. The green roof will be made from the composting of food waste generated in the building's own canteen. Therefore, the main objective of this study is to calculate the solar efficiency of a sustainable green roof, evaluate its thermal performance, and quantify the impact that its implementation would have on energy consumption and the thermal comfort of its users. The results obtained confirm that an environmentally sustainable green roof has a positive effect on summer energy consumption and that this effect is much greater when there is water on the roof, as shown by the difference in energy savings between the dry (−53.7%) and wet (−84.2%) scenarios. The data show that in winter the differences between a green roof and a non-vegetated roof are not significant. In this case, the estimated energy consumption penalty (0.015 kWh/m^2) would be 10% of the summer gain.

Keywords: green roof; energy savings; solid waste management; sustainability

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1. Introduction

High urban population growth rates, driven by industrialization, have intensified the urban pollution and caused severe natural phenomena and presenting significant risks to human health and the environment [1]. The world's urbanization ratio (urban population as a % of total population) has grown from 43.4% in 1991 to 55.7% in 2019; this requires an understanding of the multi-dimensional nature of urban development [2]. Urban sustainability is therefore becoming increasingly important due to climate change, human activities, and increasing urbanization [3].

The need to reduce urban air temperature increases and increase green spaces, especially in city centers, is serious. Added to this, there are growing concerns about the global energy crisis and waste management. As a result of the above, the 2030 Sustainable Development Strategy aims to make Europe a resource-efficient society and establishes the principle of a hierarchy of waste management options, according to which prevention is the best option, followed by preparation for reuse, recycling, other forms of recovery, and finally disposal. That is why green roofs are an environmentally sustainable option for cities to reduce the impact of urbanization.

Green roofs thus provide nature-based strategies for promoting urban environmental sustainability which include a combination of mitigating and adaptive actions mainly focused on restoring and preserving the balance between the biotic and abiotic elements of ecosystems by increasing biodiversity, developing green spaces, and promoting the sustainable development of cities by building a habitable urban area [4–6].

The world's cities are of great relevance in the global development scenario as they will become even more urbanized in the next decade [7]. They represent around 85% of total global GDP (Gross Domestic Product) while consuming approximately 70% of the world's natural resources and 70% of all energy produced, producing around 50% of all waste, and (3) producing 70% of all greenhouse gases [8].

The use of waste in construction materials and the environmentally friendly development of buildings and infrastructure are some of the mechanisms put in place to conserve natural resources and contribute to environmental and socio-economic sustainability [9]. Designed and implemented as engineered ecosystems, green roofs (GR) enhance urban sustainability by providing multiple functions and benefits. A GR system consists of a root protection and storage layer, a draining layer, a root permeable filter layer, a substrate, and plants [10]. In recent years, the scientific literature has discovered a significant number of related benefits across a wide variety of sustainability zones, which makes GR a common engineering application universally applicable to the fight against climate change [11], namely the mitigation of the urban heat island (UHI) [12,13] and improvement of urban air and water quality [14,15].

The GR is one of the technologies that have demonstrated energy reduction for cooling or heating buildings [16–19], being considered as an additional thermal insulation compared to bare or graveled roofs. However, energy savings have been found to vary considerably depending on several factors, mainly related to the site weather, the thickness of the existing insulation layer, and the type of vegetation used for the roof [20,21]. In addition to reducing UHI intensity and minimizing the extent of urban overheating, green infrastructure helps manage urban wastewater [6].

Research has shown that increasing the R-value of a building envelope does not guarantee a reduction in energy demand and can result in insufficient performance in present or future climates [22–24]. The evidence shows that climate change will have a considerable effect on the energy efficiency of a building. Therefore, it is essential to design the thermal transmittance of the building envelope for the current and future climate [25].

From a thermal point of view, the first effect of green roofs is to reduce heat transfer to the building [26–28], thereby improving indoor comfort conditions, mainly by reducing ceiling temperatures [29,30].

In terms of energy, the impacts of GRs on heating and cooling loads have also been studied in terms of their potential to reduce the UHI, as they can reduce outdoor temperatures in their vicinity in different climatic contexts [31].

In addition to the research into the impact of the reduction in ambient temperature that can be achieved by GR, a number of studies were completed investigating the insulation benefits it can provide. He and Jim [32] assesses the thermodynamic transmission in a GR based on a simulation model of the traditional Bowen Ratio Energy Balance Model (BREBM). It found that the GR captures and retains great quantities of heat to form a good thermal protection from variations. Additional work by Pérez et al. [33], shows that passive systems, due to the shading provided by the plants and the insulation provided by the plants and growing media, can be used to reduce the energy consumption of the system. Morakinyo et al. [34] presented a parametric paper of the result of four types of green roofs on outdoor/indoor temperature and cooling demand. It was found that semi-intensive green roofs were more effective than their fully extensive counterparts in reducing both outdoor temperature and cooling demand. In a similar way, Ouldboukhitine et al. [26] evaluated the heat flux through the roof. They found that, in summer, the passive cooling effect of the rooftop was three times greater with the green roof, while in winter, the green roof decreased rooftop heat loss on cold days. Rakotondramiarana et al. [35] demonstrated that GR protects the roof structure in conditions of extreme temperatures and large temperature fluctuations. The plants reduce the maximum indoor air temperature and increase the thermal comfort of the building during summer days.

Composting is considered a sustainable option for the treatment of urban organic waste and its reuse as a soil conditioner and fertilizer [36]. As well as being a rich nutrient supply for plants, including nitrogen, phosphorus, and potassium, compost is also considered to reduce the incidence of soil-borne plant diseases. These benefits make composting an excellent solution for dealing with the vast quantities of biodegradable solid waste produced in the world [37]. As such, composting can help achieve circular economy goals in both developed and developing countries [38,39].

Aerobic composting is an excellent way of transforming manure into a hygienic, humus- and nutrient-rich, stabilized, and phytotoxic-free material that has attracted the attention of national and international bodies [40,41].

Various chemical properties of the organic waste, such as excessive moisture or low porosity, can limit the efficiency of composting [42,43]. The effective composting of organic waste therefore requires good control of a number of factors for the production of a superior agricultural product [44]. These include the composition of the compost raw materials (C/N ratio, pH value, particle size, and moisture content) and the control of the process (aeration rate and temperature). These factors may have an impact on the intensity of microbial metabolism and biochemical transformation and thus on the final products [37]. Various strategies, such as aeration, raw material mixes, blowing agents, process management methods, additives and microbial inoculants are used in composting to achieve shorter composting times, reduce costs, and thus improve the quality of the final compost product [45,46].

Municipal solid waste (MSW) treatment is one of the essential services provided by any city. Neglecting its needs can be problematic for the city's inhabitants. The rapid growth of cities and the resulting growth in urban populations have caused a significant expansion in the generation of municipal solid waste (MSW) [47]. The trend towards sustainable waste management (WM) according to the Reduce, Reuse, Recycle, and Recover (4 R) principle is growing worldwide [48,49]. Universities are also becoming more concerned with initiatives to mitigate their environmental impacts [50]. University campuses can make a significant contribution to the general sustainability of their local communities. They reduce the environmental impact of the traditional model and encourage healthy and sustainable living within the campus community [51].

The organic component of mulch substrates is effective in maintaining vegetation and increasing water retention. These organic materials are not always available locally. It is therefore important to design and use locally produced growing media as this reduces the financial and energy costs of transport [52]. The incorporation of local waste materials is preferable as it transforms low-value materials into a valuable material, clearly lowering costs and helping to promote the implementation of green roofs. Today, there is a need for a holistic approach to waste management (WM) in university campuses. Composting food waste (HWW) to create a green roof on campus can reduce the adverse environmental effects and be part of a circular economy. The compost can serve as a substrate for the green roof and then be added as fertilizer, ending the waste cycle. Applying this type of waste strategy brings campuses closer to the goals of carbon neutrality and sustainability [53].

In this work, the design of an environmentally sustainable vegetation cover was proposed from the substrate originating from the composting of food waste generated in the canteen of the building itself. This project proposes an extensive green roof with low maintenance and no need for irrigation. This is a future construction on the non-trafficked roof which houses the building's ventilation installations and, since it is an already constructed building, it is necessary for the vegetation cover to be light, shallow, and suitable for the previously constructed concrete support structure.

The aim of this work is to calculate the solar cooling/heating efficiency of a sustainable green roof. The presented study uses the solar efficiency method, which simplifies the complex physical models of heat transfer and radiation on green roofs to calculate the marginal cooling or heating performance. This is an indicator of the performance of innovative passive solutions that can be installed on the last layer of the building surface with respect to solar radiation. The calculation of these solar cooling and heating performances requires the calculation of the conduction heat transfer, i.e., the energy balances of the outermost surface of the building, in this case, the roof. This allows the temperature of this surface to be estimated, which in turn allows greater accuracy in estimating the heating and cooling requirements.

Thus, it is intended to meet the following objectives:

1. A more energy-efficient building;
2. An improved and landscaped building and an attraction for the university community and citizens with the following agenda: reflecting the commitment of the UPV/EHU to the needs of Basque society as well as those derived from its history and its socioeconomic, political, and cultural transformations; disseminating the knowledge of universal culture and science; and exercising its daily activity in an economically, socially, and environmentally sustainable manner (UPV/EHU Strategic Plan 2022–2025). The new plan defines the public university as "a decisive agent for the development of the Basque community" as well as "a space for the generation of new ideas";
3. The valorization of waste generated in the canteen of the same building through composting in pursuit of the principles of openness and dissipation of ecosystems, hierarchy, self-sufficiency, and zero waste.

This work would represent a step forward for the UPV/EHU in the 2030 strategy through the analysis of the possible implementation of composting as a waste management measure.

2. Materials and Methods

2.1. Experimental Site Description

The experimental roof site for this study is located in Bilbao (4315.8522° N, 256.9635° E) in the north of Spain. Bilbao is the largest city in the north of Spain and the tenth largest city in Spain, with a population of about 347,000 inhabitants in 2023. The urban area of Bilbao has 1,037,847 inhabitants, making it the largest populated urban area in northern Spain. It has an urban area of 18.22 km^2. The Bilbao School of Engineering is located in the San Mamés area next to the San Mamés football stadium, the EiTB headquarters, and the bus station (Termibús).

The building that houses the Faculty of Engineering in Bilbao is located between the San Mamés stadium and the access to Bilbao (see Figure 1), which, being a busy road, has an acoustic barrier along the side of the building. The building is also clad with a ventilated façade along which the UPV/EHU logo is displayed. The part of the roof of the EUITI-EUITMOP building where the vegetation cover will be installed has a total surface area of 1106.55 m^2.

Figure 1. View of the study area from above.

The climate is atlantic; rainfall is very abundant and almost always exceeds 1000 mm. In addition to being abundant, rainfall is well distributed throughout the year, with a maximum in autumn–winter and a minimum in summer, although no month receives less than 30 mm. The 150–160 days of annual rainfall mean that, on average, it rains every other day. Rainfall intensity is low. Under these conditions, the relative humidity is high throughout the year (80–90%).

Average temperatures are mild, ranging from 12° to 13°. The average temperature in January does not fall below 6 °C and in July it does not exceed 20°, giving a temperature range of 9–11 °C. Summers are mild with very rare periods of extreme heat.

All environmental conditions were measured throughout the year using the weather station located on the roof of the Faculty of Engineering building in Bilbao. On the other hand, the indoor conditions are kept constant at 20 °C and 25 °C for the summer and winter seasons, respectively.

In an extensive vegetation cover, the substrate is particularly important as it provides nutrients, water and oxygen, filtration, and physical support for the vegetation. It is therefore the key element that determines the success of the implementation of a green roof. This substrate layer, together with the drainage and filtration layer, forms the so-called rooting layer of the green roof system.

A meteorological station was placed at a height of 2.5 m above the roof, a. Air temperature and relative humidity (HMP155A-L, Campbell Scientific Ltd., Shepshed, UK) as well as rainfall (TE525L, Campbell Scientific Ltd., Shepshed, UK) were measured and recorded every 30 min on a data logger (CR850, Campbell Scientific Ltd., Shepshed, UK).

Various studies [54] recommend that the percentage of inorganic components in the green roof substrate should be greater than 80% to reduce the overall weight of the roof [55]. The use of 100% compost should also be avoided in extensive roofs as this could lead to the smothering of the vegetation, encourage weed growth, and increase the load on the roof, compromising the long-term success of the project.

The roof drainage quality is also influenced by the substrate, the vegetation, and the age of the green roofs. The growing substrate, which could be either inorganic, organic, or a specific mix of the two, is a critical component of the design of green roofs. Appropriate substrate materials need to have appropriate water and nutrient retention properties as well as adequate drainage and lightweight and chemical balance to provide support for the plants' regulatory functions [56,57]. To meet these conditions, substrates are frequently evaluated according to key physical and chemical properties such as bulk density, weight, porosity, particle size, water retention capacity, pH, and organic matter. The desired ecosystem of the green roof is also important for selecting the appropriate amount and type of organic components for the growing media [58].

Green roof growing media are usually made up of the following elements:

- Perlite is a material obtained as a result of the thermal treatment of volcanic siliceous rock of the rhyolite group at 1000–1200 °C. It is presented as white particles whose dimensions vary between 1.5 and 6 mm with a low density and are generally less than 100 kg/m^3. It has a water retention capacity of up to five times its weight and a high porosity; its pH is close to neutral (7–7.5);
- Vermiculite is obtained by exfoliating a type of mica at temperatures above 800 °C. It has an apparent density of 90 to 140 kg/m^3 and is supplied in 5–10 mm flakes. It can hold 350 L of water per cubic meter and has a good aeration capacity, although it tends to compact over time. It can contain up to 8% assimilable potassium and up to 12% assimilable magnesium. Its pH is close to neutral (7–7.2);
- Sand: The grain size of the sand ranges from 0.5 to 2 mm in diameter. Its bulk density is similar to that of gravel. Its water retention capacity is medium (20% by weight and more than 35% by volume); its aeration capacity decreases over time due to compaction;
- Gravel has a diameter of between 5 and 15 mm and an apparent density of between 1500 and 1800 kg/m^3. It has good structural stability; its water retention capacity is low although its porosity is high (more than 40% of the volume).

Taking all of the above into consideration [59–61], the substrate to be used will be a mixture of 20% compost from the Faculty of Engineering canteen waste, 30% perlite, 20% vermiculite, 10% sand, and 20% gravel from reclamation.

This mixture will be spread around the selected perimeter of the roof to be landscaped by pouring, raking, and lightly compacting. The plants will be planted on this substrate. The roof will be provided with a water inlet so that, at the time of application, the substrate mix will have sufficient humidity to work on the roof and prevent it from drying out and avoiding wind erosion.

The plants to be selected are weather resistant and will allow for minimum maintenance which will avoid installing an irrigation system and allow the reuse of rainwater, thereby providing an extra element to the environmental quality.

Figure 2 shows a schematic section of the green roof to be installed on the roof of the UPV-EHU building together with its components. The first layers are the vegetation and the substrate which is composed of 20% compost and can absorb excess moisture to prevent the roots from rotting. The drainage layer made of polyethylene absorbs excess water and the root barrier prevents plant roots from damaging the material. Part of the rainwater is recollected by the drainage layer and is available for use during dry periods. The insulation layer between the vegetation and the roof slab acts as a temperature barrier for the plant roots, in this case, 5 cm extruded polystyrene.

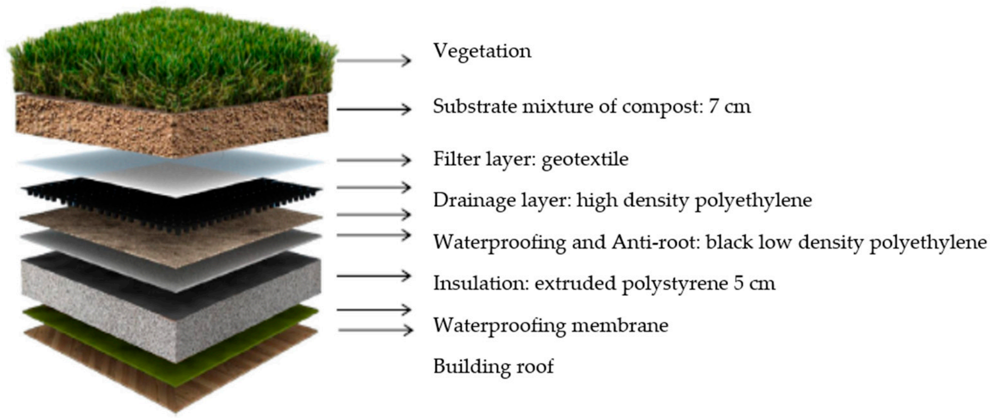

Figure 2. Composition and layers of green roof.

2.2. Waste Measurements

Local composting is seen as a sustainable option for bio-waste recovery and is increasingly demanded by society. University campuses are no exception. In Bilbao, as in many European cities, growth and development have led to a lack of green spaces. Consequently, one of the problems to be solved in the case of composting organic waste generated in the university canteen would be the distribution of the compost produced. For this purpose, the composting and its subsequent distribution will be carried out on the green roof of the building itself.

Measurements [62] have shown that in the canteen of the university building about 8.1 tons of waste were generated per academic year and that the percentage of organic waste, excluding wooden boxes but counting bread, was equivalent on average to about 60% of the mass of waste generated.

Waste from the building's canteen is currently separated into the following fractions: waste, packaging, and glass with varying degrees of efficiency and, according to the latest count (Table 1), about 33 kg of organic waste per day or about 5 tons during the academic year. These data are consistent with other authors who have found that higher education institutions (HEIs) generate an average of 0.08 kg/day per capita. Between 22% and 55% of the total waste generated in HEIs is usually biodegradable organic material [63]. Therefore, the total production rate is calculated to be 89.50 g/user/working day [64].

Table 1. Waste accounted for in kilograms after the implementation of waste minimization and management measures per day.

Sample Number	Organic (No Bread) (kg)	Bread (kg)	Packages (kg)	Total (kg)
1	31.8	3.7	10.0	45.5
2	27.2	1.5	5.6	34.3
3	35.7	4.2	10.9	50.8
4	27.4	2.8	10.0	40.2
Average	30.5	3.1	9.1	42.7

It must be taken into account that during composting, organic matter tends to decrease due to its mineralization and the consequent loss of carbon in the form of carbon dioxide; these losses can represent almost 20% by weight of the composted mass [65].

According to RD 506/2013 of 28 June on fertilizer [66], the organic matter content of compost must exceed 35%. In the study by Montejo et al. [67] in which 30 compost samples from 10 different composting plants were analyzed, it was found that the average organic matter content was close to 45% while the average density of the resulting compost was 1.06 g/cm^3.

Considering all these aspects, it was calculated that the volume of compost that can be produced during the academic year is 8.39 m^3.

In view of the above, this work proposes the design of a green roof on the building itself, using a substrate produced by composting the food waste generated in the building's canteen. The aim is to make efficient use of the organic fraction and to obtain high-quality compost through selective separation at the source.

2.3. Calculation of Green Cover Efficiency

This section begins by explaining the solar efficiency methodology used to calculate this indicator of the performance of a green roof in relation to heat gains due to solar radiation. This is conducted by defining the theoretical maximum and minimum temperatures of the external surface of the green roof. These two theoretical extreme temperatures, together with a calculated external surface temperature, are related by an efficiency parameter relative to solar radiation.

The concept of plant cover efficiency is applied whereby the thermal performance of plant cover for specific environmental conditions can be quantified in a simple way. In this study [68], in the energy balance of the outermost layer of the building it was shown that, since the qcond value is negligible compared to the sum of the values of shortwave radiation, longwave radiation and convective heat exchange occur in the outermost layer of the roof or façade. In this way, it is possible to accurately estimate the value of the temperature in the outer layer (T_g) by simply applying the energy balance at the outermost surface of the building envelope, without taking into account the term qcond in the energy balance when solar radiation is present.

Therefore, efficiency is defined as the radius between two temperature differences:

$$\varepsilon = \frac{T_{max} - T_g}{T_{max} - T_{min}} \text{ (-)} \quad (1)$$

where T_g represents the temperature in the outer layer of the substrate and T_{max} and T_{min} represent the limits of this temperature.

Depending on the period in which one wants to study the efficiency of the roof, T_{max} and T_{min} will represent the best or the worst possible scenario. In summer, the efficiency will be maximum when the temperature in the outer layer of the substrate (T_g) is equal to the minimum temperature (T_{min}). On the contrary, in winter the best scenario is found when T_g is closest to T_{max}, therefore the optimum value of the efficiency during winter will be equal to 0.

- T_g is the measured temperature of the exterior surface of a monitored building. It might be a vertical or a horizontal component [69].

In buildings with passive elements, such as green systems or ventilated facades, where complex heat transfer phenomena such as evapotranspiration and natural and/or forced ventilation can occur, the choice of the layer in which T_g is to be estimated is crucial. Once T_g is known, the solar efficiency equation can be used to accurately model the heat flow through the component with this complex behavior.

In the absence of a green roof installed at the Bilbao School of Engineering, we have studied the thermal behavior of a green roof based on the work carried out by Erkoreka [70] which allows us, in a simple way, to quantify the thermal performance of a green roof for specific environmental conditions. The model presented by Sailor [71] was taken as a starting point and the following simplification was made in order to obtain this simplified model for the calculation of T_g under specific working conditions; the water content in the substrate and in the drainage layer, the evapotranspiration rate, LAI, albedo, photosynthetic rate, convective heat transfer from the roof to the outside air, and heat flow through the substrate were considered constant or insignificant.

The simplified model is reflected in the following equation:

$$T_g = T_{out} + \frac{\alpha_{effective}\, G_{solar}}{h_{heat-mass,\, effective}} \text{ (-)} \tag{2}$$

where T_{out} is the outdoor air temperature [°C], G_{solar} is the global solar radiation incident on the surface [W/m^2], and $h_{heat\text{-}mass}$ is the effective transfer of the coefficient heat mass [W/(m^2 C)].

- The maximum temperature (T_{max}) can be calculated using the experimental method provided by ASHRAE [72] which calls it $T_{sol\text{-}air}$.

$$T_{max} = T_{sol-air} = T_{out} + \frac{\alpha \cdot G_{solar}}{h_{comb}} - \frac{\varepsilon \cdot \Delta R}{h_{comb}} \text{ (°C)} \tag{3}$$

where T_{out} is the outdoor air temperature [°C], α is the absorptivity of the surface for solar radiation, G_{solar} is the global solar radiation incident on the surface [W/m^2], h_{comb} is the combined coefficient of heat transfer by long-wave radiation and convection at the outer surface [W/(m^2 °C)], ε is the hemispherical emissivity of the surface (-), and ΔR is the difference between the long-wave radiation incident on the surface from the sky and the surroundings and the radiation emitted by a hypothetical blackbody at outdoor air temperature [W/m^2].

According to ASHRAE, the maximum possible $T_{sol\text{-}air}$ temperature is obtained when:

- The term α/hcomb has a value of 0.052, which represents the usual maximum value for this term;
- The term (ε·ΔR)/hcomb has a value for horizontal surfaces facing the sky of 4 °C and for vertical surfaces of 0 °C;
- While the minimum temperature, considered as the 'wet bulb temperature', can be obtained using the outdoor temperature and relative humidity [73], T_{min} is defined as the temperature of the air when it is adiabatically saturated with water, in which case its temperature will decrease to the temperature called the wet bulb temperature. This, in turn, can be calculated as a function of the outdoor air temperature and the relative humidity, using the following empirical algorithm [74].

$$\begin{gathered} T_{min} = T_{wet-bulb} = T_{out}\, atan\left[0.151977\ (RH\% + 8.313659)^{\frac{1}{2}}\right] + \\ atan(T_{out} + RH\%) - \text{atan}(RH\% - 1.676331) + 0.00391838\ (RH\%)^{\frac{3}{2}} \cdot \\ atan(0.023101\ RH\%) - 4.686035\ (°C) \end{gathered} \tag{4}$$

2.4. Calculation of the Energy Demand after the Installation of a Vegetation Cover

This section presents an estimate of the energy required by a cooling/heating system to maintain comfort conditions assuming the installation of a green roof. For this calculation, only the heat flow through the roof has been taken into account.

For this analysis, the location of the building (Bilbao) was taken into account. In order to achieve greater accuracy in the calculations, the information collected by the meteorological station located on the roof of the UPV/EHU Faculty of Engineering building in Bilbao has been used; this information includes measurements of the external air temperature, the relative humidity of the external air, rainfall, and solar radiation.

Once the temperatures of the outer layer of the vegetation cover of GR had been determined, we then estimated the solar efficiencies throughout the whole year using the meteorological data collected during 2021 at the weather station located on the roof of the building of the Faculty of Engineering in Bilbao. The methodology used was as follows.

The energy required per square meter is equal to the heat flow through the roof. This can be expressed in the following equation:

$$\frac{q}{A} = U\left(T_{in} - T_g\right)\ (\text{W}/\text{m}^2) \tag{5}$$

where T_{in} is the temperature inside the building. According to thermal comfort standards, this value is 25 °C for summer and 20 °C for winter. T_g is the temperature in the external layer of the substrate. On this occasion, it was calculated based on the efficiency values developed in Equation (1) above. This would become:

$$T_g = T_{max} - \varepsilon\left(T_{max} - T_{min}\right)\ (^\circ\text{C}) \tag{6}$$

U (W/(m^2 °C)) is the thermal transmittance including the thermal resistances of the insulation layers under the vegetation cover:

$$U = \frac{1}{R_{si} + \frac{e_1}{k_1} + \frac{e_2}{k_2} + \cdots + \frac{e_n}{k_n} + R_{se}}\ (\text{W}/(\text{m}^2\ ^\circ\text{C}) \tag{7}$$

where R_{si} and R_{se} are the surface thermal resistances of the enclosures in contact with the outside air, $e_1 \ldots e_n$ are the thicknesses of the different layers, and $k_1 \ldots k_n$ are the thermal conductivities of the respective materials. According to the Spanish regulations CTE [75], Bilbao is located in climate zone C1. In the same basic HE energy saving document, the maximum limit of thermal transmittance of roofs in contact with the air is defined for the different climatic zones.

The following assumptions were made in the model.

The growing part of the substrate was considered a homogeneous layer of 5–6 cm. The substrate may be dry, partially saturated, or fully saturated with water. This degree of saturation determines the conductivity and thermal capacity of this layer. The reference value for the thermal resistance of the green roof is taken as 0.44 (m^2 °C/W) [18].

The geotextile filter of less than 2 mm was considered to have negligible heat transfer.

The drainage layer was the most complicated to model as it is the only non-homogeneous layer. The effective thermal conductivity concept described by Çengel [76] was used. This concept assigns an effective thermal conductivity to a non-homogeneous layer such that the actual thermal resistance is the same as that modeled as homogeneous with this effective thermal conductivity.

The insulating layer is made of 5 cm extruded polystyrene (k = 0.03 m °C/W) which provides a thermal resistance of 1.66 (m^2 °C/W) to the green covering.

The impermeable layer was assumed to be a homogeneous 5.85 mm thick layer, 2.85 mm 'preflex', and 3 mm 'graviflex' with negligible heat transfer.

3. Results and Discussion

3.1. Efficiency Result and Meteorological Conditions for a Dry Summer Period

In the summer test period, from 20 March to 22 September, sunny and dry days were considered when there was no water available to the plants either in the drainage or in the growing substrate layers. This is likely to occur after at least a week has passed since the last rainfall on sunny spring and summer days.

Representative days were chosen for comparison and to show differences in solar efficiency: (Figure 3 from 19 June to 5 July. In addition, to better understand the influence of weather conditions on solar efficiency, the temperature, rainfall, and solar radiation during those periods were also plotted.

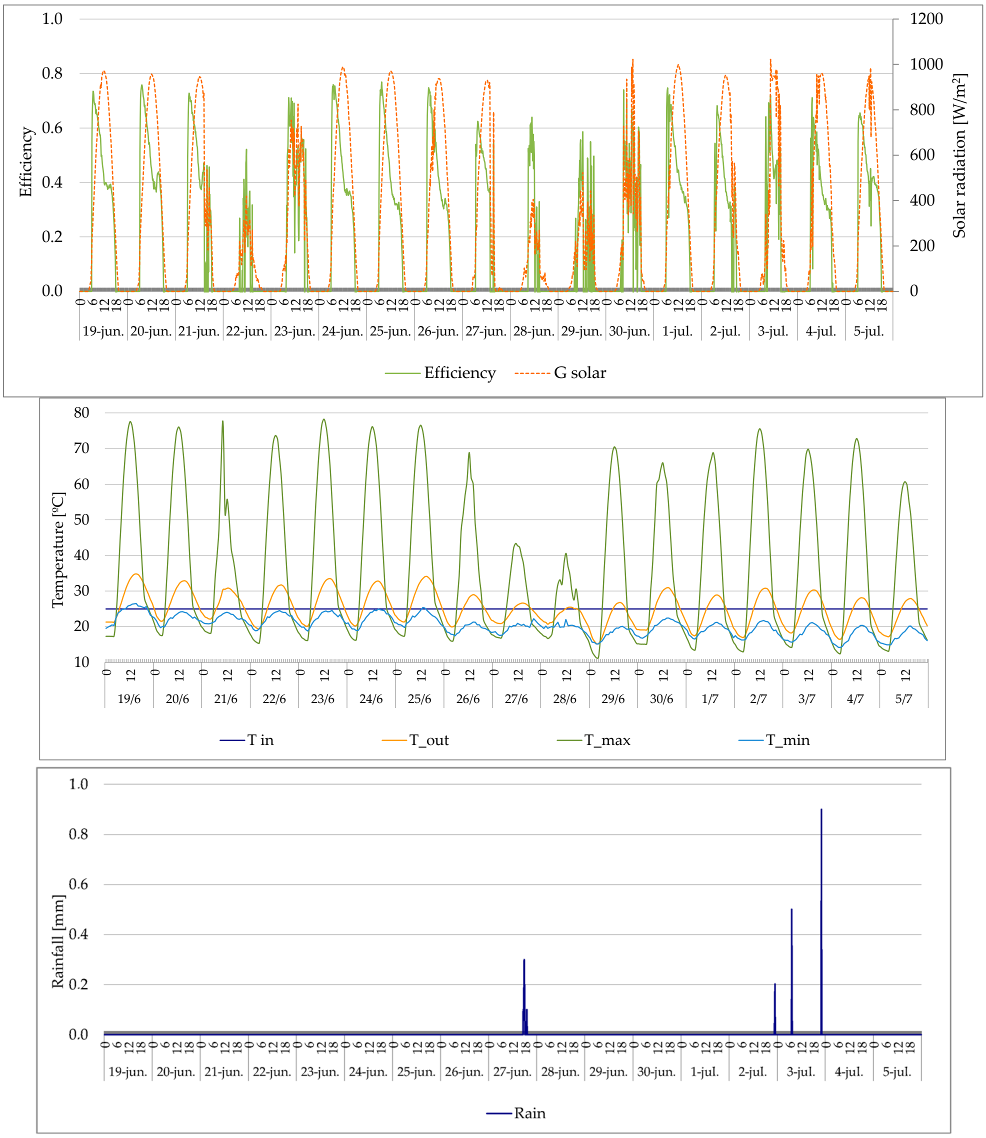

Figure 3. Evaluation of the solar efficiency and solar radiation. The evaluation of the interior air temperature, outside air temperature, maximum temperature, minimum temperature, and rainfall data registered form 19 June to 5 July. (Sharp fluctuations in solar radiation are due to cloud movement).

In Figure 3, the efficiency is analyzed over a period of 15 days. A number of results can be seen. Firstly, there is a noticeable difference between cloudy and clear days. On sunny days, the solar efficiency reaches values of more than 0.75; on cloudy days, the values drop significantly to 0.60. This is mainly due to the fact that on clear days the solar radiation curve is bell-shaped (e.g., 19–21; 24–26 June), reaching its peak around noon. However, on cloudy days the measured solar radiation is irregular (e.g., 22; 28–30 June).

Taking a look at the precipitations during the reference periods, we can assume the absence of water in the green roof with the exception of a limited number of showers on a few days. To obtain a standard value representing the green roof efficiency for this scenario, it was necessary to calculate a daily average from the hours when the efficiency is calculated. Averaging the total dry period efficiency values, we obtained a representative value for the solar efficiency in dry summer conditions: ε = 0.64.

3.2. Efficiency Result and Meteorological Conditions for a Wet Summer Period

For the second scenario, a wet summer, we considered sunny days where there is abundant water available for plants in the drainage and in the growing media layers. This is likely to happen on sunny days of spring and summer just after heavy rainfall events.

To show differences in solar efficiency, representative days were chosen (Figure 4): from 15 to 31 July 2021.

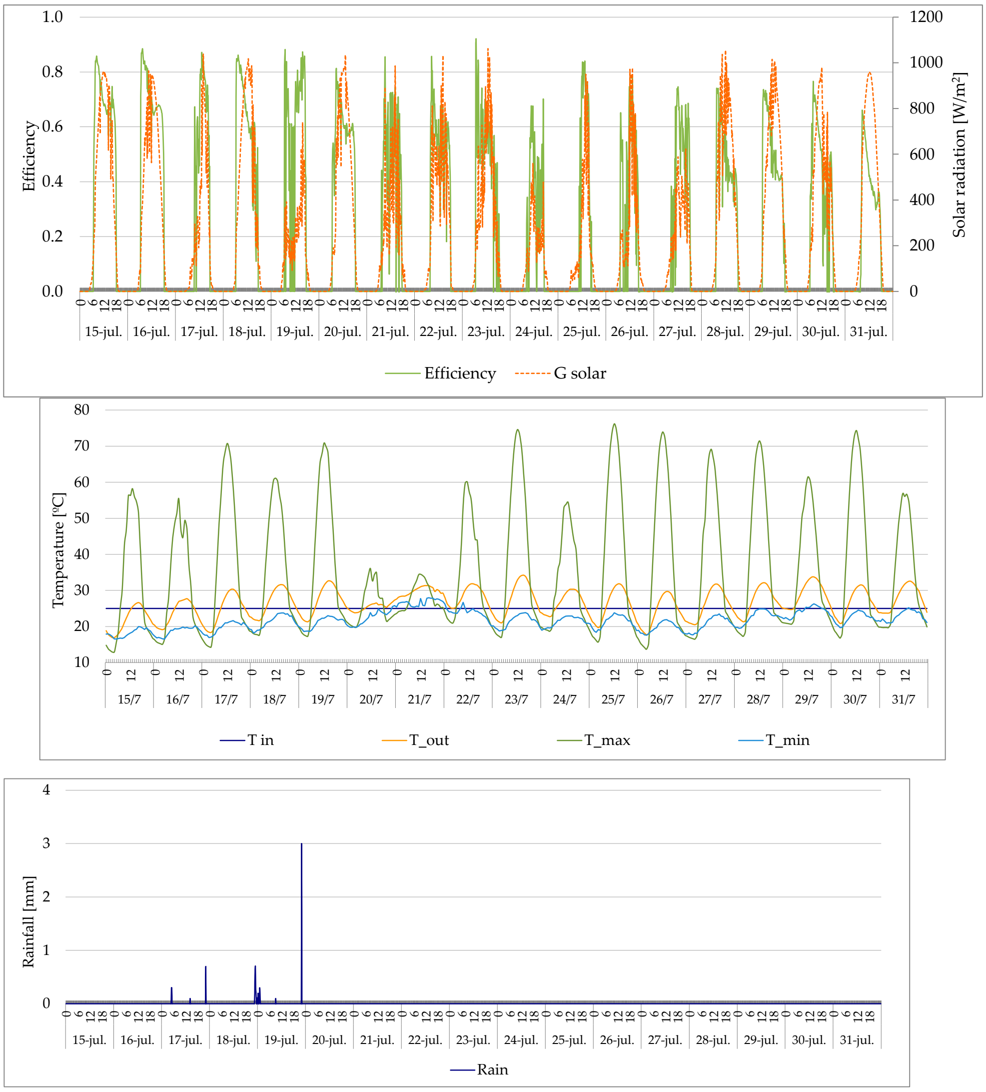

Figure 4. Evaluation of the solar efficiency and solar radiation. The evaluation of the interior air temperature, outside air temperature, maximum temperature, minimum temperature, and rainfall data registered from July the 15 to the 31. (Sharp fluctuations in solar radiation are due to cloud movement).

If we look at Figure 4, we can see that after a period of rainfall on 19 July, the efficiency of the roof reaches a peak close to 0.9 (ε = 0.90 [-] or 90% cooling efficiency) on the following days, including 23 and 24 July, which were clear days. Similarly, there is a less abrupt drop in efficiency, which remains close to 0.8 throughout the day. On the other hand, we can see in Figure 4 that, on days when the vegetation cover is practically dry, its efficiency includes maximum values close to 0.72 (ε = 0.72 [-] or 72% cooling efficiency). This shows the fundamental role played by the water content due to the phenomenon of evapotranspiration in the thermal behavior of the roof.

There is a small increase in efficiency in the days following a period of rainfall, indicating the influence of the said rainfall on the efficiency of the roof. This shows that the water content in the plants and in the substrate is the key to achieving greater benefits.

In order to obtain a representative standard value for the efficiency of the green roof for the wet summer scenario, the daily average of the whole scenario was taken. The average of the values obtained during the wet summer season gives a representative value of solar efficiency under these conditions: ε = 0.80.

The green roof provides an effective and environment-friendly result to solve such problems as the internal temperature change during summer and winter [77].

From these considerations, it can be seen that a better result will be obtained when the vegetation cover is saturated with water. It is clear that it is advisable to have a GR, especially in hot seasons since the cooling efficiency value represents the goodness of the GR solution in reducing the temperature below the vegetation layer.

3.3. Efficiency Result and Meteorological Conditions for a Wet Winter Period

For winter conditions, we considered cold days in autumn and winter in which there is plenty of water available for the plants and in the drainage and soil layer. This is likely to happen in autumn and winter during and after rainy days. It was necessary to subdivide the analyzed period into clear and foggy days since foggy days imply a specific distribution of solar radiation. Atmospheric conditions such as clouds, pollution, and fog generally increase the portion of diffuse radiation. On an extremely overcast day, almost 100% of the solar radiation is diffuse.

Figure 5 shows the distribution of the solar efficiency over a 15-day cold period and the distribution of temperatures, solar radiation, and precipitation. The figure shows that when it rains on a sunny day, the solar efficiency increases to values of 1.1. This phenomenon is due to changes in the humidity and incident solar radiation which alter the physical properties. In addition, the temperatures T_{min}, T_{max}, and T_{out} are very close to each other on cloudy days. However, on sunny days the temperature difference between T_{out} and T_{max} can reach very significant differences of up to 15 °C.

Analyzing Figure 5, at around 12:00 the highest potential solar air temperature can be calculated from Equation (6), taking into account the fact that the locally monitored solar radiation would be 30 °C compared to an outdoor air temperature of 18 °C and a wet bulb temperature of 14 °C. This is because during the cold season, the outdoor air temperature and the minimum temperature are very similar on cold and sunny winter days (see Figure 5); although, T_{out} is slightly higher than T_{min}. It should be noted that the wet bulb temperature and the air temperature are similar when the air temperature is low. The solar efficiency data are kept at around 0.85. A cooling efficiency of 85% implies a heating efficiency of only 15% during the cold season. Analyzing the whole period of the cold wet season gives a value of 0.90 for solar efficiency.

It is important to note that on wet cloudy winter days, T_{out} will be similar to T_{min} (wet bulb temperature). This effect is due to thermal inertia: on foggy days, the solar radiation is very low and the nights are usually cold in Bilbao. The ground layer is likely to cool down during the night and, as the fog does not allow enough solar radiation to reach the roof, it will not be able to heat it above the wet bulb temperature. It is important to note that the wet bulb temperature and the air temperature will be very close when the air temperature is below 5 °C.

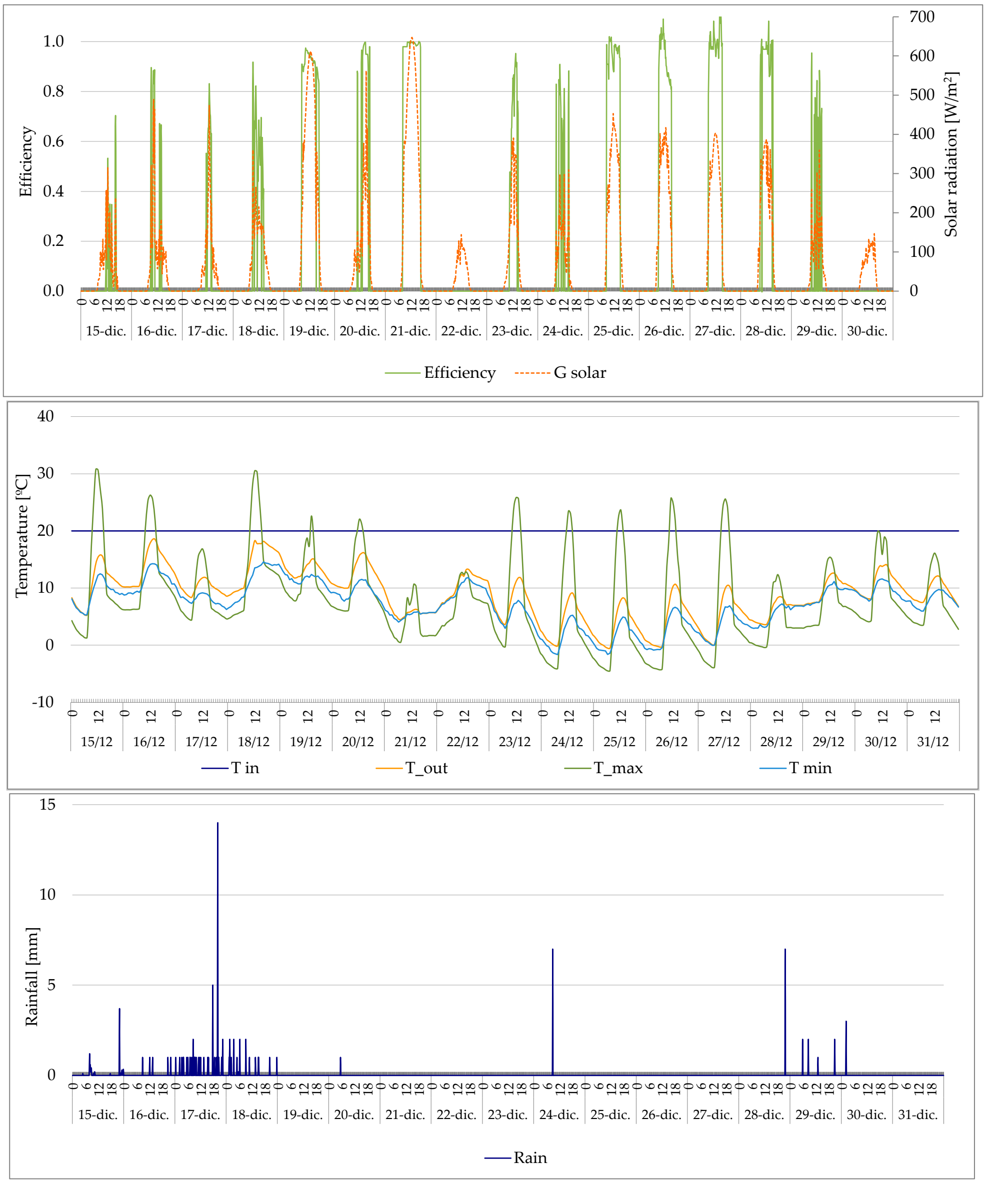

Figure 5. Evaluation of the solar efficiency and solar radiation. The evaluation of interior air temperature, outside air temperature, maximum temperature, minimum temperature, and rainfall data registered from 15 to 31 December.

Figure 5 shows that, during the cold and sunny winter period, the outside temperature at 12:00 h during this period does not exceed 14.3 °C, which would probably require heating inside the building. With a cooling efficiency of 90%, the GR solution will create unwanted cooling on the outer surface of the roof which will create an additional heating demand inside the building. Therefore, during the cold season, it would be preferable to have a skin solution that allows a higher temperature to be achieved on the outermost surface of the roof.

3.4. Energy Savings of a Sustainable Green Roof

Once the efficiency values were known, and using the data collected during a whole year by the weather station located on the roof of the Faculty of Engineering in Bilbao, the temperature of the outer layer of the vegetation cover throughout the year was estimated. From this temperature, the heat flow through the green roof was calculated.

Defining efficiency for the green roof, it is possible to study the heat flux passing through the different layers of the roof and consequently estimate the amount of energy required by the cooling and heating system to maintain the comfortable hygrometric conditions inside the considered building.

For comparison with the heat flow corresponding to the future situation with vegetation cover, it has been considered that the temperature outside the vegetation cover will be equal to T_{max}. For the wet winter period, the comparison of the heat flux with the current situation has only been carried out for the scenario without cloud cover as there is considered to be no variation in the flux between the unvegetated and the vegetated cover when the incidence of solar radiation is small.

In each season, the different conditions of the green roof were analyzed and compared to obtain an idea of the magnitude of the difference in terms of energy savings. They represent two limiting situations in which the realistic behavior of the green roof can be found. The energy required by the heating/cooling system per hour was calculated for each day of the two macro-seasons considered, using the data provided by the recorded weather data from the building's meteorological station. From these calculations, we can extract two types of results: the energy consumption per square meter for the whole season, obtained by summing all the hourly values [kW/h], and the maximum absolute value of power needed among all the calculated ones [W/m^2].

These two values will help to quantify the direct energy savings and the peak energy achieved will quantify the savings in terms of the cost of the plant.

We considered the heat flux per square meter [W/m^2] entering the roof; therefore, we determined the power required by the cooling system as positive and the heat leaving the roof and the power required by the heating system as negative.

3.4.1. Summer Period

The calculations regarding summer were performed considering the period of the year in which the cooling system (A/C) is normally used to maintain the indoor temperature at the fixed value of 25 °C. It usually goes from 1 May to 31 October.

The temperature of the layer underneath the vegetation (T_g) is calculated for the interval of time in which the solar radiation is substantial; otherwise, the calculation of the T_{max} becomes meaningless. In this section, the minimum value of 150 W/m^2 for the solar radiation was chosen.

With the weather data collected for the whole year period, we were able to calculate the soil external surface temperature once T_{min} and T_{max} had been calculated. Since T_g is a function of the efficiency and since we found two different summer values for the said efficiency, we have to calculate two different temperatures of the soil for dry and wet conditions. They represent, respectively, the worst and the best conditions in which the roof can be found with respect to the water content.

In Figure 6, the second half of July has been taken as the reference period in which to observe the two temperatures for the two scenarios. The dry summer conditions are denoted in yellow, the wet conditions are in green, and the internal temperature which must be stably maintained at 25 °C inside the building is in blue. The solar radiation has also been plotted to obtain an idea of how it affects the evolution of the temperatures plotted above. It has been observed that the dry temperatures are always higher than the wet ones. This necessarily implies a greater benefit from a roof that is constantly wet.

This GR system, if correctly watered, is very effective in reducing summer cooling requirements resulting from heat gain from opaque elements of the building envelope. During sunny hours, the outermost layer of the building can be kept very close to the ambient wet bulb temperature.

A significant number of studies have demonstrated the benefits of GR in reducing the energy required for heating and cooling, which in turn reduces energy consumption and increases thermal comfort. Green roof is an important contributor to energy efficiency [78–80].

Heidarinejad and Esmaili [81] studied the green roofs' passive cooling and thermal insulation, demonstrating their potential to reduce energy consumption for cooling a building. On the same issue, the performance of green roofs in spring was highest in mild climates with higher average temperatures where the evaporative cooling of green roofs could compensate for the cooling energy [82,83].

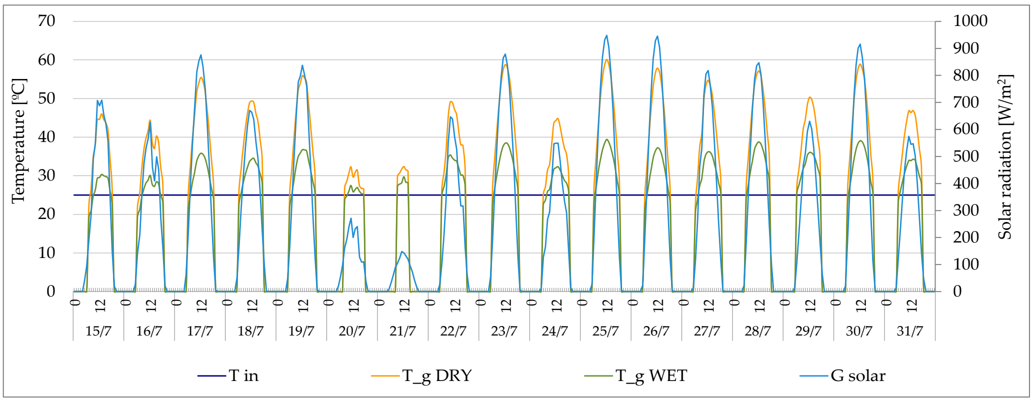

Figure 6. Temperature of the internal air, the external surface for dry and wet summer, and the solar radiation from 15 to 31 July.

It is clear from the considerations that it is advisable to have a green roof, especially in the hot seasons, as the efficiency value represents the capacity of the roof to reduce the temperature under the layer of plant cover (T_g). The reduction in the temperature of the outermost layer of the green roof improves the thermal comfort of the interior of the building [30,84,85].

It was necessary to quantify the amount of energy required by the studied building to maintain the comfort conditions inside. In this way, we can use the information obtained about the efficiency and therefore the heat flux through the building's insulation layers in order to obtain the energy requirement.

Using the temperatures calculated in the previous section, we can calculate the daily thermal cooling load required to maintain the internal temperature at the hygrometric comfort standards set for summer (25 °C).

The energy was calculated using equation 5 and then plotted for the whole period. By considering only positive values for the heat, this means that $T_{in} > T_{out}$, so we are only considering the heat that enters the building and therefore when the cooling system is needed. In Figure 7, both the cooling loads required in the wet and dry cases have been plotted to allow comparison.

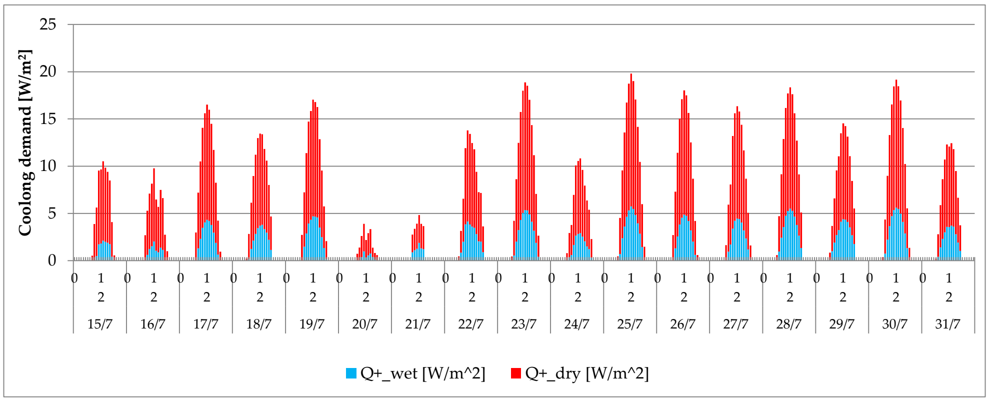

Figure 7. Cooling demand per square meter (only considering the positive value) from the 15 to the 31 of July.

As can be seen in the figure above, the difference in cooling energy demand between the wet and dry scenarios is very significant. The peak cooling demand for the dry condition is 5 W/m^2 on average. However, in the dry condition this demand increases significantly to an average of 15 W/m^2 which means that three times more energy is required to achieve the same indoor comfort conditions.

The energy savings from installing a green roof can therefore be calculated. In this case study, the average daily energy saving for the dry vegetation scenario is estimated to be 0.092 kWh/m^2 which represents a reduction of 53.7% in the energy required to cool the building. On the other hand, the daily average energy consumption for the scenario in which the vegetation cover is saturated with water is 0.144 kWh/m^2, which represents a significant saving in consumption related to the cooling system of 84.2% less than for a traditional roof.

Green roofs reduce energy consumption in the warm season which is consistent with the findings of Kostadinov et al. [86] who found that green roofs in summertime increase the thermal efficiency of the roof by 57% and decrease the thermal transfer. Dwijendra et al. [87] showed that the presence of a green roof, as opposed to a normal roof, has the capacity to decrease a building's energy consumption by 30.7%. The majority of the findings agree with the literature on green roof systems, justifying them as a good passive cooling technology.

3.4.2. Winter Period

The winter calculations were carried out taking the period of the year when the heating system can normally be used to maintain the internal temperature at the fixed value of 20 °C into account. The period considered is from 23 September to 19 March (plotted from 15 to 31 December). The temperatures of the layer below the vegetation (T_g) are calculated in a period in which solar radiation is significant; otherwise, the calculation of T_{max} becomes meaningless.

In winter, when radiation is slightly lower than in summer, a minimal radiation of 50 W/m^2 was selected. After calculating T_{min} and T_{max} and with consideration of the meteorological data recorded every hour of the period, we can calculate the external surface temperature of the ground.

It is important to note that on a sunny winter day there is less incident solar radiation on horizontal surfaces than on a summer day.

Figure 8 shows the heating demand required to maintain thermal comfort inside the building once the green roof is installed. It can be seen that every day the set temperature is higher than the outdoor temperature, so heating is required to maintain indoor comfortOn some sunny days when the outdoor temperature is around 15 °C, e.g., 15, 16, and 18 December, the heating demand is lower. On colder days, the heating demand peaks at up to 8 W/m^2.

In the same way, the Figure 8 shows that the average heat flux thanks to the vegetation cover remains at an average value of 3.7 W/m^2 which means an energy consumption of 0.030 W/m^2. The results indicate that the installation of a green roof would increase the energy consumption of the heating system by 0.015 kWh/m^2 per day. This is because during winter the waterlogged vegetated cover repels more solar energy than a non-vegetated cover.

A comparison of the two periods, namely summer and winter, shows that the increase in energy consumption in winter is only 10% of the total savings that can be achieved in summer. This is consistent with the limited amount of research that has investigated the thermal performance of green roofs in cold winter conditions [88–91]; in general, they found a moderate thermal advantage for green roofs in colder climates but a much smaller advantage in warmer climates.

Green roofs had only a small negative (i.e., cooling) effect on the urban heat island surface in winter, as reported by Teemusk and Mander [92], but in diurnal periods the existence of green roofs, caused surface cooling and low evapotranspiration even during winter weather periods, can cause this cooling in the green roof system [93] comparable for a green roof to [94]. However, the green roof had a higher average surface temperature of about 1 °C. This meant that it had a beneficial (i.e., warming) role at night compared to the traditional roof. This is probably caused by its substrate, which has a high heat capacity and thermal inertia, allowing the surface to cool more gradually during the night.

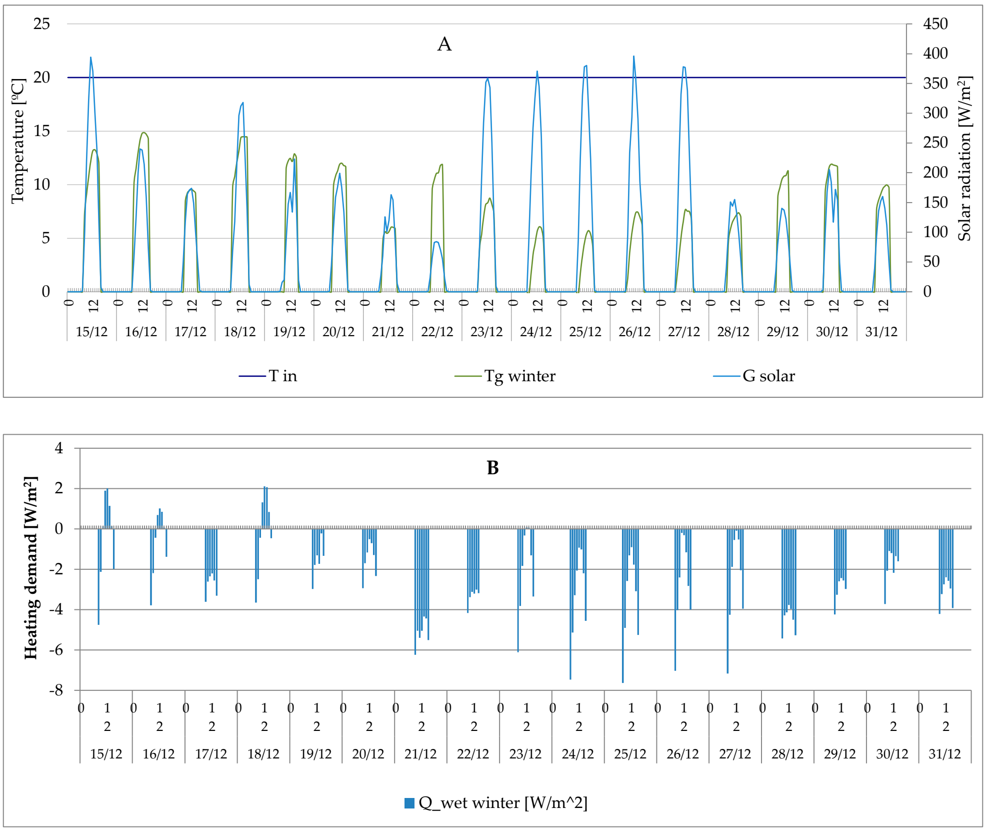

Figure 8. (**A**) Temperature of the internal air, the external surface during wet winter, and solar radiation. (**B**) Heating demand per square meter from the 15 to 31 of December.

3.5. Limitations

The efficiency of this sustainable green roof for the EHU building in Bilbao was calculated according to that of a green roof in Vitoria. As the water use of the green roof depends on the precipitation and the evaporation process of the soil, as well as on the transpiration and photosynthesis of the vegetation to produce carbohydrates, the data from Bilbao were used to calculate the available water so the efficiency was estimated as being slightly above the real value.

4. Conclusions

This study investigates food waste from students in university canteens and analyzes its use as compost to create green cover on campus to reduce energy demand. It was found that food waste in the university canteen consists mainly of organic matter, bread, and packaging. Composting on the UPV-EHU campus can treat about 80% of the organic waste generated by the canteen. This strategy of composting organic material in the canteen involves multiple stakeholders and joint efforts by university officials, canteen managers, and students. Thus, the integration of organic waste management and sustainable vegetation cover in the urban context becomes possible.

With all this, the study of the solar efficiency was carried out over a whole year. The cooling efficiency for summer was found to be 75%. On the other hand, in winter the GR cooling efficiencies were found to be close to 90%. This means that the heating efficiency of this skin solution is only 10%. In other words, the temperature of the exterior surface will be much closer to the minimum possible temperature. This means a reduction in the temperature of the outermost part of the roof during sunny hours which will lead to a corresponding increase in the heating requirement and higher energy costs. In winter, the thermal performance of this skin solution is of no interest because of the cooling effect generated by evapotranspiration. This prevents solar radiation from heating the outermost surface of the building envelope.

The results obtained confirm that in terms of energy consumption, an environmentally sustainable green roof would have a positive effect in summer, with this effect being notably more pronounced when water is present in the roof. The average heat flux through the saturated green roof was found to be about 10 W/m^2 lower compared to a traditional roof. There is a significant difference in the summer energy savings achieved by the green roof between the dry and wet scenarios, reducing energy consumption by 53.7% and 84.2%, respectively. This evidence suggests that it would be desirable to install an irrigation system in climates with low rainfall.

On the other hand, the data show that in winter the differences between a vegetation cover and a non-vegetation cover are not significant. In the most unfavorable situation, the disadvantage for the green roof is minimal. In this case, the estimated energy consumption penalty (0.015 kWh/m^2) would be 10% of the summer gain. This is because during the day the plant's evapotranspiration cools the outer surface of the roof, increasing energy consumption. However, during the night it acts as an insulator by reducing the convective heat loss through the roof, thus helping to keep the building warm.

Spreading the practice of composting and the visibility of green roofs would be another important outcome of the project, including external visits and training to learn and control composting processes. In this way, chemical fertilizers could be replaced by the compost produced and a greater knowledge of green roof systems and direct contact with nature could be provided locally and as part of the university community.

Finally, it should be noted that the advantages of implementing a green roof go beyond the economic sphere. Bearing in mind that the building where the green roof is to be installed is a public university, the most important aspect is probably its didactic and exemplary value.

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