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Article

Lifecycle Analysis of Green Roofs in the Mediterranean Climate

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Abstract: Buildings account for a significant amount of energy consumption and greenhouse gas emissions worldwide. Electricity and fossil fuels are currently the primary sources of energy used for cooling and heating buildings, depending on the climate and location. Both energy sources are responsible for significant greenhouse gas emissions. In contrast, plants and vegetation absorb carbon dioxide and, thus, improve the quality of air. This effect indirectly influences climate change to lower energy demands and produce additional emissions due to rising energy consumption trends. Plants also reduce the ambient temperature by providing shade on roof surfaces. Hence, the large-scale deployment of green roofs reduces energy consumption, emissions, and costs. However, green roofs also impact the overall weight of a building and require additional construction costs. Therefore, the contribution of green roofs to the various structural and thermal performances of buildings varies for extensive intensive or semi-intensive systems. These interactions warranted a lifecycle analysis to optimize the extent of green roof applications. This approach highlighted sustainability performance measures, including energy, emissions, water, and waste. The presented study addressed a lifecycle analysis of green roof deployment during a hot summer in a Mediterranean climate zone. This climate applies to many areas that benefit from warming temperatures without extreme needs for cooling or heating. The emphasis on comparing two towns within the same climate zone facilitated a more detail-oriented approach to the lifecycle analysis. The results illustrated the energy consumption and associated release of greenhouse gas emissions related to structural and roofing materials and thermal operations throughout the service life of a building. The conclusions assessed the challenges and opportunities of green roof applications on new and existing buildings.

Keywords: green roofs; energy consumption; lifecycle analysis; greenhouse gases; emissions

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1. Introduction

Nature-inspired architectural designs and modern plant breeding strategies aim to enhance resilience to extreme climates and promote efficiency in utilizing energy, materials, water, and light within the built environment [1]. The concentrations of gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other halocarbons are rising in the atmosphere due to anthropomorphic activity, according to observations from global monitoring stations [2]. These gases are collectively known as greenhouse gases because they influence climate warming [2]. Buildings account for a substantial portion of both the energy consumed worldwide and the greenhouse gases emitted. This contribution was reported to be 32% in 2010 for energy and one-third for greenhouse gases [3]. The share of the construction and operation of buildings in carbon dioxide emissions reached 37% in 2015 [4]. Despite a temporary decline due to the COVID-19 pandemic, global emissions reached a 37% share in 2021 [5,6]. The predicted trend of further increases between 2020 and 2060 is nearly 0.7% per year [7]. Carbon dioxide is the prime greenhouse gas produced by human activities [8]. Greenhouse gases contribute to climate change due to rising temperatures [8]. Cement production also releases carbon dioxide into the atmosphere [8], and thus, it raises concerns about construction. Buildings account for a substantial portion of both the energy consumed worldwide and the greenhouse gases emitted [9].

Additionally, due to the use of halocarbons, CFCs, HCFCs, and hydrofluorocarbons (HFCs) as insulation materials, cooling agents, and refrigerants, the buildings and construction sector is also a substantial source of non-CO_2 GHG emissions [9]. Local measures have indicated that the peak urban electric consumption increases between two and four percent for every one °C increase in the daily maximum temperature above the range of 15 to 20 °C [10]. Hence, the process of using energy to cool buildings impacted by global warming causes progressive degradation of the climate [11]. While the primary objective for local authorities in many cities is to achieve environmental benefits with green roofs, it is crucial for the constructors and engineers involved in designing such roofs to consider the thermal advantages they offer [3].

The energy consumption of buildings has roots in the direct operations of heating, ventilation, and air conditioning to maintain an interior that is as comfortable as possible and to produce electricity to maintain human comfort and support everyday activities such as lighting, elevators, and water circulation, all of which results in rising global CO_2 emissions [12]. Depending on the climate and location, electricity might be used as the energy source for cooling and operating appliances in buildings, while some nations use fossil fuels for heating [13]. Both sources significantly contribute to carbon emissions, disregarding regional differences [14]. Encouraging and rewarding policies effectively promote energy-efficient and climate-resilient structures, and hence, they reduce the increases in greenhouse gas (GHG) emissions [14]. The most severe outcome of climate change is rising sea levels, which may cause extensive interruptions such as flooding [8]. Therefore, reducing energy consumption has broader benefits in climate resilience [15,16]. These benefits are vital for developing communities that are struggling with balancing environmental footprints with energy demands [17].

1.1. Effects of Green Roofs on Buildings

The adoption of vegetation and other natural elements benefits communities [18]. Developing shaded areas lowers ambient temperatures, reducing energy consumption and operation costs [19]. Plants and vegetation also absorb carbon dioxide and improve air quality. This contribution indirectly decreases energy use [19].

Green roofs lower the temperature of an exterior roof surface in nearly all climate zones [20]. As an example, the implementation of green roofs in the heat island area within Beijing's Fifth Ring Road has resulted in a 52.55% reduction in the high-temperature zone and a 29.17% reduction in the sub-high-temperature zone when compared to an area without green roof construction [21]. For instance, an examination of a two-storey building in the United States revealed that a green roof could reduce heat flux by anywhere from 18% to 50% compared to a standard flat membrane roof. Additionally, a simulated analysis of a green roof on a five-storey office building in Singapore indicated annual energy savings ranging from 1% to 15%, depending on the specific attributes of the green roof [22]. In warm periods when there is sufficient solar radiation, the presence of vegetation, plant transpiration, and the cooling effect of evaporation from the ground all work together to lower external surface temperatures during the daytime [23]. Initial albedo measurements for roofing materials have indicated that green roofs exhibit a low albedo. An albedo is the portion of the incoming radiation reflected from the surface. However, the cooling effect of a green roof is not solely attributed to its albedo; it also results from a combination of factors, including insulation, evapotranspiration, and shading [24].

Further, dark surfaces (e.g., concrete and asphalt) and a lack of vegetation can raise the level of warmth in metropolitan areas, and hence, vegetation contributes to climate resilience [10]. Although green roofs are possible for pollution management and dropping indoor temperatures, it is vital to consider several variables [25]. The cost of developing green roofs might be a significant drawback compared with conventional roofs. This drawback is due to their unique design, which includes many more layers than a standard roof, and the fact that they are built using expensive imported materials [26]. Hence, the surcharge weight of a green roof is a challenging parameter [18]. This extra self-weight demands higher load capacity and a more robust structure [26].

Green roofs may also contribute to food security in various communities [27]. However, this lifecycle evaluation was primarily concerned with the energy advantages of different green roofs. Case studies have shown that green roofs reduce energy consumption and greenhouse gas emissions across multiple climate zones requiring heating and cooling [28]. However, when energy demands are low and roof replacement cycles are short, the impacts of the materials used to build a green roof are vital for the feasibility of such a project [29]. This vitality explains the public policies in some municipalities offering subsidies and tax relief to encourage the initiation of green roofs and offset their initial cost [10].

A roof garden is an excellent approach to improving buildings in urbanized areas through landscape design. Converting unused roof spaces into sites offering ecological benefits and economic opportunities for landscaping purposes is valuable in dense cities with limited economically viable spaces [30]. The annual patterns of rainfall–runoff associations in the case of green roofs are notably affected by the thickness of the surface layers. This observation suggests that incorporating green roofs can substantially diminish rainfall runoff at the regional level and within individual buildings [1]. Enhancing architectural aesthetics and views are additional uses of green roofs [31]. The predicted service life of a green roof is between 40 and 55 years, in contrast with conventional roofs, which last roughly 20 years [10].

Green roofs offer numerous benefits; however, it is essential to acknowledge their drawbacks. For instance, these drawbacks encompass narrower selections of suitable plant varieties, potential aesthetic concerns (especially during the winter months), increased roof loads, elevated costs, and the implementation of more intricate roofing systems, among others [32].

1.2. Roof Garden Types

The International Green Roof Association (2013) has defined extensive, semi-intensive, and intensive green roof types (Figure 1). Extensive green roofs are appropriate for low-maintenance and slow-growing vegetation. Semi-intensive green roofs have more options because of their deeper ground levels. Hence, short grasses, herbaceous perennials, and shrubs fit this type, but trees and tall bushes are impractical. Intensive green roofs suit various plant types, from lawns to trees. These roofs can also accommodate extra amenities, such as walkways, seats, playgrounds, and ponds [30].

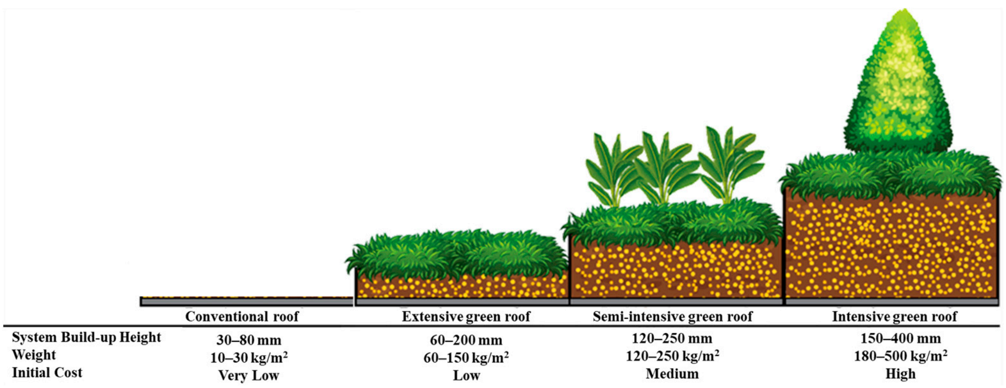

Figure 1. Different types of green roofs and their characteristics (reproduced and revised after [33]).

Many studies have examined the influence of growing media characteristics, including moisture, density, and thickness, on green roof thermal properties [33]. These studies have demonstrated substantial reductions in energy consumption and heat flow for soil depths of 10 to 20 cm compared to conventional roofs [33,34]. Hence, the type of species and required growth media thicknesses are vital for green roof performance evaluations.

1.3. Significance of the Research

Applying green roofs and their impacts on energy consumption is virtually viable for any climate zone. However, the feasibility of maintaining proper vegetation limits the practical applications of green roofs. Further, thermal insulation benefits in very cold or hot climate zones are trivial and not necessarily specific to green roofs and their growth media. Therefore, it is essential to focus on moderate climate zones, where the significance of research relies on finding an optimized approach to green roof applications. Prior studies have suggested the feasibility of such optimization for conventional buildings [35]. This study follows a general bottom-up approach to assessing green roof applications in buildings, highlighting the thermal performance, energy consumption, and greenhouse gas emissions influenced by direct heating and cooling operations and indirect embeded material footprints. The results of those studies and the presented literature review warranted a more comprehensive approach to applying green roofs in moderate climates, highlighting an optimized solution. This study examined the studies of green roofs in Madrid, Spain, and it compared the results with similar scenarios in Rome, Italy. These results are extendable to similar cities with Mediterranean climates (Köppen climate classification: Csa) [36]. This climate type has moderate winters and warm-to-hot summers. The research hypothesis stated that buildings utilizing rooftop gardens experience cooler indoor temperatures due to natural shading. Additionally, rooftop gardens minimize the heat energy loss via the roof, slowing the release of heat and lowering the demand for cooling or heating using the performance of a modeled building with a rooftop garden [28].

2. Methodology

The adopted methodology of this study was the simulation of the thermal performance of a conventional building concerning the application of different green roof systems and an analysis of impacts on energy consumption and greenhouse gas emissions. EnergyPlus^{TM} is a sophisticated building energy simulation tool with a green roof model [37]. The presented analysis utilized this tool as the simulation platform for investigating the green roof effect on the thermal performance of a building [11,38]. Hourly energy consumption in the modeled building followed user-specified construction, internal loads, schedules, and weather [39]. EnergyPlus simulates energy flows based on interior and outdoor environmental conditions. The flows involve heating, cooling, lighting, ventilation, and other functions [38]. EnergyPlus's modular design is especially well-suited for adding new features [39]. The input data included a building input data file (IDF), which contained all the study case's features, and a weather data file, which included information on the location's climate. The choices of locations, Rome, and Madrid, were close enough in climate to justify the same building types and materials as described in the following sections.

2.1. Building Model

The choice of material was based on templates from the Open Studio software, a module of the EnergyPlus platform, for the given climate zone 3C, equivalent to the Csa classification for selected cities [40]. The presented building model had three floors with two units in each building, and each unit's area was 110 m^2 (i.e., the average apartment area in Italy). The building contained 24 windows, 8 of which were 1.3 m^2, and the other 16 were 1.3 by 2 m. These windows provided 93.5 m^2 for each house. This architectural design represented a typical apartment building in a constrained urbanized area such as Rome or Madrid, the capital cities of Italy and Spain, respectively [41].

2.2. Environmental Analysis

Figure 2 exhibits the monthly low, average, and high temperatures of Madrid and Rome in 2021 from the NOAA, indicating the relative differences between the low and high values [42]. Madrid has slightly colder average temperatures, nearly 14%, compared to Rome, but it experiences substantially more significant differences between its high and low temperatures, nearly 234%. The presented research used this data as an example of the possibilities for using the adopted methodology. The analyses were scalable to include data variations concerning climate, location, and time.

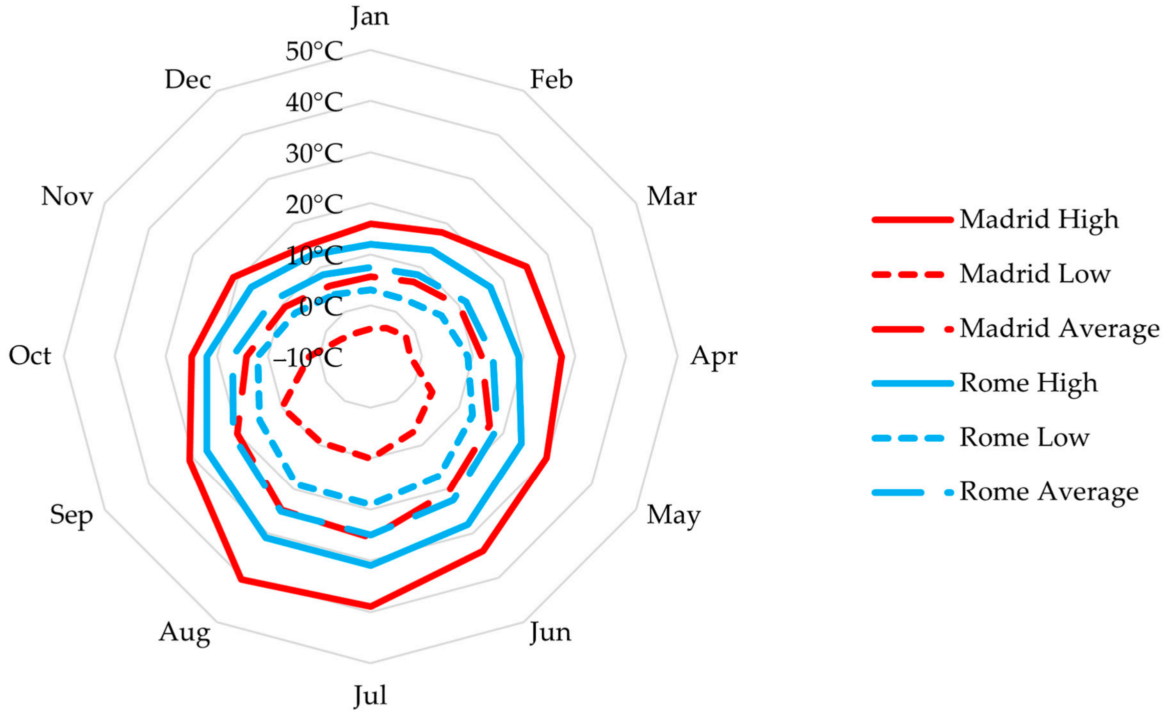

Figure 2. The monthly low, average, and high temperatures of Rome and Madrid.

The selected heating, ventilation, and air conditioning (HVAC) system was a packaged terminal air conditioner (PTAC) based on the residential occupancy of the building chosen and the 3C climate zone [40]. The energy sources for heating and cooling were gas and electricity, respectively. The air-conditioning system worked with setpoint temperatures of 19 °C for cooling in the summer and 28 °C for heating in the winter [43].

2.3. Thermal Properties

The growing media was a mixture of compost and lightweight expanded aggregate. Lightweight aggregate acts as insulation and drainage media [44,45]. The lightweight aggregate is a product of expanding shale, clay, or slate in a rotary kiln at a temperature near 1100 °C [44,45]. The invigoration of the roots and the soil improvements might be noted as advantages of applying lightweight aggregate [46]. The growing media included 30% lightweight aggregate, 7% compost, and 63% crushed filler by weight. This mixture had a thermal conductivity of 0.272 W/m/K, a bulk density of 858.7 kg/m^3, and a specific heat of 1140 J/kg/K [28]. Various combinations of ingredients and the choice of lightweight aggregates were available to balance these properties for our purposes. A 45-year life span was assigned to the green roof options [29]. Figure 3 demonstrates the relative plant height and growing media thicknesses for the roof types. Similarly, Figure 4 exhibits the thicknesses of the roofing components, except for the insulation (49 mm in all cases) and the substrate (100, 350, and 700 mm for the extensive, semi-intensive, and intensive green roofs), which are not shown for clarity. Table 1 includes the input values for the simulation of the green roof performance using EnergyPlus [28,47]. Table 2 lists the carbon dioxide sequestration of the green roof materials [48].

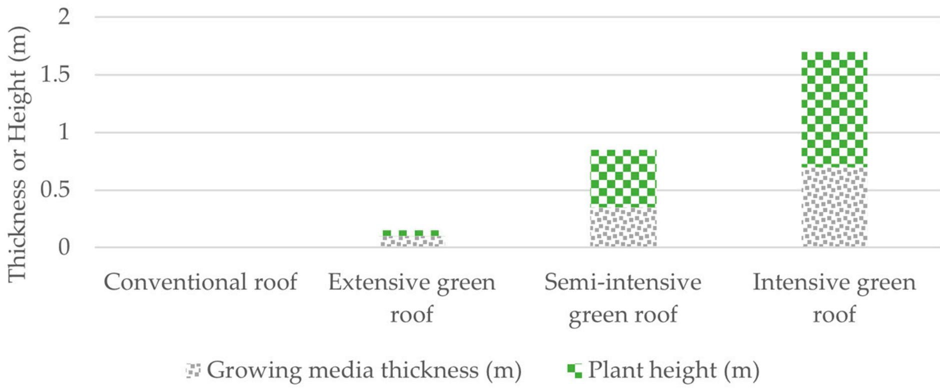

Figure 3. Soil thicknesses and plant heights for the different green roofs.

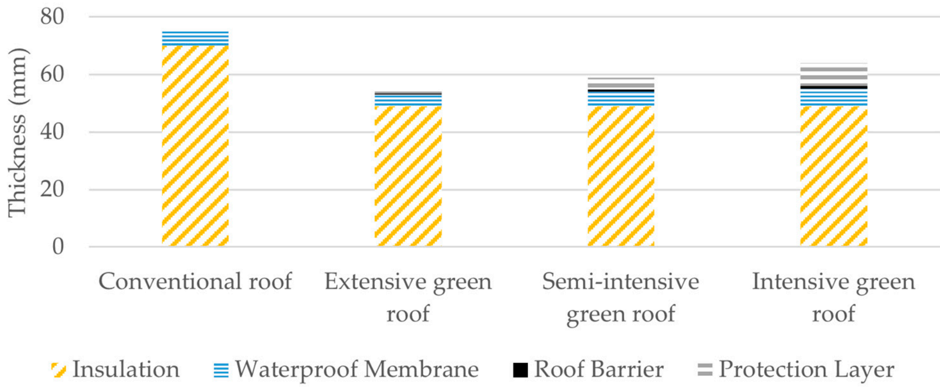

Figure 4. Roofing components (substrate not shown for clarity).

Table 1. Inputs for the different layers of a green roof (adopted from Kalantari et al. 2023 [35]).

Material	Description	Energy (kWh/kg)	Emissions (kg CO_2/kg)	Density (kg/m^3)
Insulation	Polystyrene foam	24.58	6.12	33.7
Waterproof membrane	Bituminous membranes	0.56	0.64	1100
Root barrier	Polyethylene	23.57	3.27	920
Protection layer	Polypropylene	20.93	3.64	905
Substrate	63% crushed brick, 7% compost, and 30% lightweight aggregate	1.01	0.294	858.7

Table 2. Carbon dioxide sequestration (adopted from Kalantari et al. 2023 [35]).

Green Roof Type	Annual Emissions Reduction (kg CO_2/m^2/yr)
Extensive	0.55
Semi-intensive	1.39
Intensive	2.77

3. Results

3.1. Energy

The analyses addressed four cases of conventional buildings without green roofs and the types of extensive, semi-intensive, and intensive green roofs. Figure 5 compares the total energy used in buildings in Rome and Madrid with different roofs. The electrical and natural gas sources represent cooling and heating operations, respectively. This figure distinguishes a conventional roof as the highest and an intensive green roof as the lowest in terms of energy consumption. However, this observation for total energy primarily reflected that the heating energy as the electrical energy consumed for cooling was substantially less than the heating energy consumption. In this comparison, the extensive roofs used more electricity than the conventional roofs. The analyses showed that insulation contributed more to the cooling systems than the type of green roof. This observation was based on the defined thicknesses for the insulation and waterproofing components in conventional and green roofs. The insulation and waterproofing membrane thicknesses in the modeled conventional roofs were more than those in the extensive roofs and near those in the semi-intensive roofs, but they were less than those in the intensive roof.

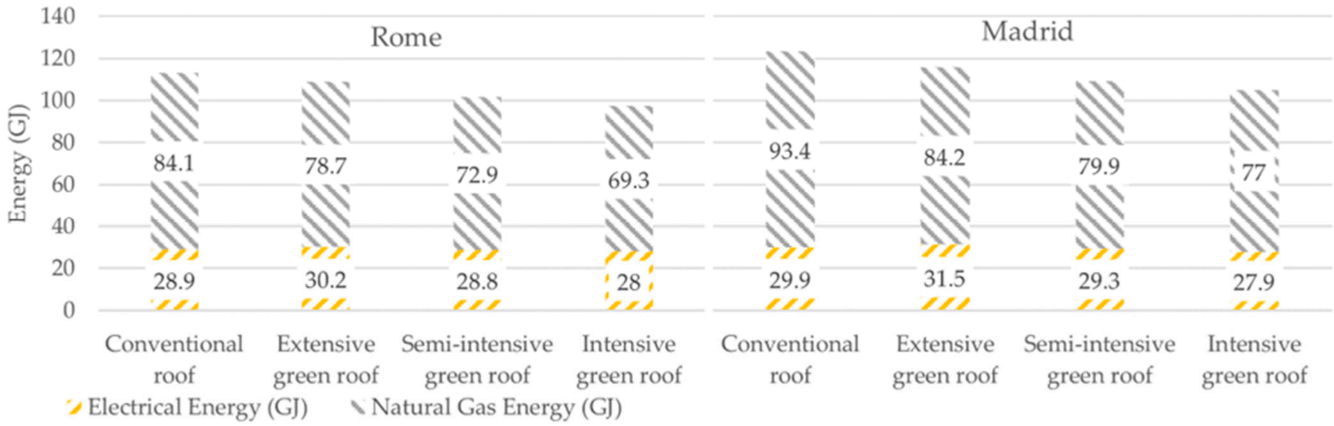

Figure 5. Total HVAC energy consumption.

Figure 6 compares the energy savings for each category of the cooling and heating operations using green roofs. The results revealed that all green roofs contributed to heating energy consumption. However, only the intensive green roof provided meaningful savings in electrical energy consumption. Regardless, these contributions were vital considering that the effects of climate change on the increasing rates of electricity consumption for cooling buildings will highlight any savings in this category.

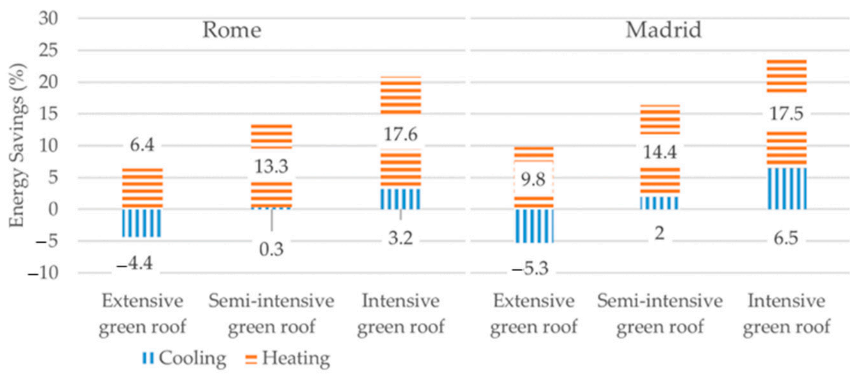

Figure 6. Energy savings associated with green roofs.

Compared to traditional roofs, the more significant electricity usage observed in the extensive green roofs could be attributed to their thicker insulation layers. According to research by Koroxenidis et al. (2016), an insulation layer's effect on thermal insulation is more significant than that of a green roof [28].

Figure 7 summarizes the greenhouse gas emissions associated with the energy consumption in the selected buildings. These results compared the savings from operational energy with the embodied energy of the roofing materials. This comparison indicated that the energy saved in the extensive and semi-intensive green roofs was more than the energy embedded in producing the green roofs and the supporting structure. The input energy was close to energy savings in Rome and Madrid. The difference between the saved and input energy values was higher for Madrid than for Rome concerning all the green roof types, including the intensive roof. Moreover, the presented comparison followed the yearly results to include the buildings' overall thermal performances, disregarding the optimum values occurring in a month.

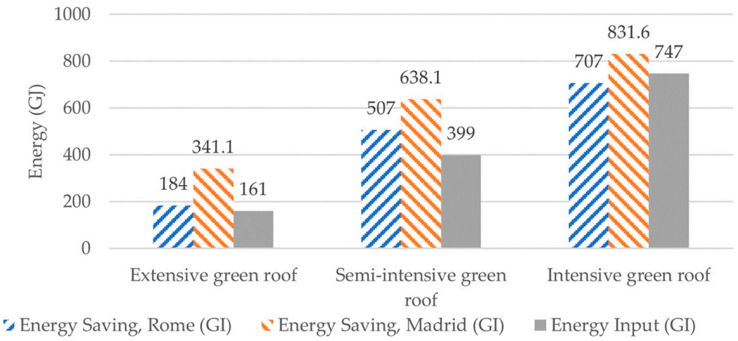

Figure 7. Energy savings and energy inputs for the different roof gardens.

3.2. Emissions

The calculation of emissions followed the life cycle assessments, including the production processes and maintenance practices. These embedded emissions were comparable with the reductions in emissions due to the performances of the green roofs. The declines had their roots in the atmospheric carbon dioxide sequestration of the vegetation and plants using the leaf area index and carbon dioxide associated with the heating and cooling energy savings. Figure 8 indicates the total carbon dioxide during the 45-year service life of each type of roof garden. Based on this diagram, it could be concluded that all the green roofs offset the effects of carbon dioxide during their lifetimes. Like the energy observations, the emissions reductions were higher in Madrid than they were in Rome. Considering the similar average temperature values in Rome and Madrid, the plant types and their sequestered emissions were identical for the presented emissions comparison.

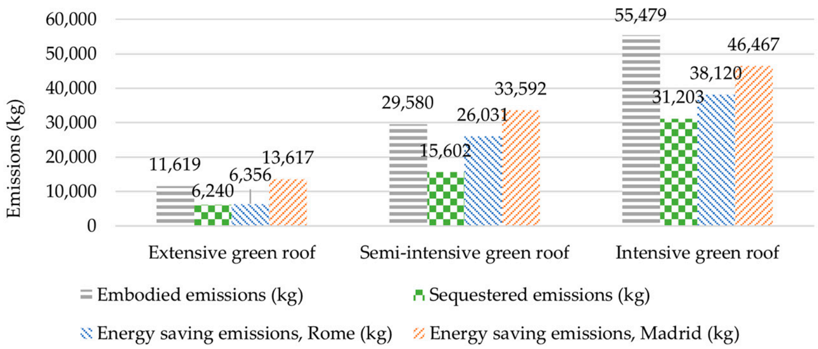

Figure 8. Emissions reductions and embedded emissions in the different roof gardens.

4. Discussions

Figure 9 compares the payback times for the carbon dioxide emissions. This comparison revealed that the semi-intensive green roof optimized the benefits for the given case study. Further, a comparison between the energy and the emissions indicated that the energy savings required slightly more time than the assumed service life to offset the input energy. The highest payback time, 48 years in Rome, was within the suggested green roof service life range of 40 to 55 years. All other values were substantially lower than the estimated 45-year service life, indicating net positive energy and emissions. The contributions from more intense vegetation and plants reduced the payback time for emissions compared with energy. All payback times were lower for Madrid than for Rome due to the higher fluctuations between the low and high temperatures, resulting in 15–46% faster payback for the energy and 11–37% faster payback for the emissions, depending on the green roof type.

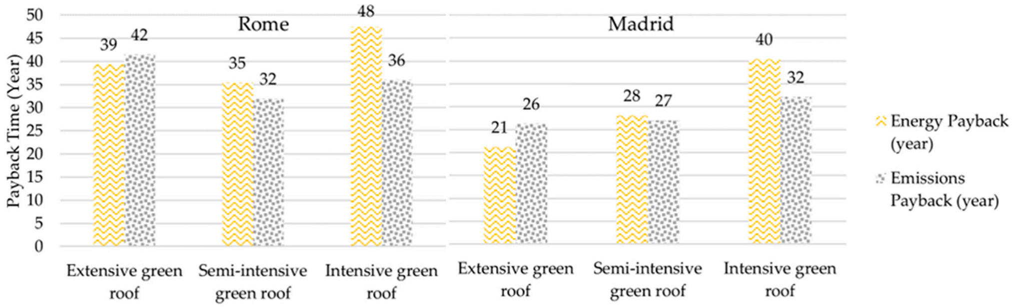

Figure 9. Payback times for the energy and the emissions.

It was vital to consider the interaction between the geometry and design of the presented case study and the deployment of the green roof types. The thermal insulation benefits of any green roof type are limited to the roof surface of a building, regardless of the number of floors. Hence, it is understood that the thermal performance of a green roof has a more substantial impact on a low-rise than a mid- or high-rise building. However, the same difference applies to the effect of a green roof on the embodied energy and emissions of structural materials as the weights of green roofs have more impact on low-rise than mid- or high-rise buildings. Another factor in balancing these effects is the thermal performance of the surrounding walls and openings, which may be a weak link for energy waste. In this case, the application of green walls could mitigate such deficiencies. An assessment of the performance of a green wall can adopt a similar approach to what has been described in this study concerning thermal performance, structural weight, and total energy and emissions.

5. Conclusions

This study investigated the energy consumption and CO_2 emissions during the installation and use of a green roof and assessed the energy savings and emissions reductions from energy savings and carbon sequestration. The results indicated that green roof systems offset emissions during their service lives. This effect contributes to atmospheric CO_2 reductions and climate change mitigation.

A comparison of green roofs showed similar results for energy savings for the extensive and semi-intensive green roof types, exceeding the input energy associated with their production and maintenance processes. However, the input energy of intensive green roofs needs more time to be compensated during their target service lives than other green roofs. The emissions reductions also reduce the need for cooling and may contribute to offsetting the required energy for green roofs, including intensive types.

The time required to compensate for the energy input and CO_2 emitted from the construction phase for all green roof types was typically lower than their expected service lives, indicating net-positive energy savings and emissions reductions. The payback time for the emissions was shorter than that for the energy for semi-intensive and intensive green roofs due to the sequestered carbon emissions in the vegetation and plants. In the case of Rome, a semi-intensive green roof indicated an optimized solution with the least payback time. The trends for Madrid were slightly different, and they exhibited shorter payback times than those for Rome.

The conclusions of this analysis warrant future studies to consider the plant types, irrigation systems, building types, and broader impacts on financial and social benefits due to the limitations of this study.

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