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Archives of Environmental Protection
Vol. 52 no. 1 pp. 136–146

PL ISSN 2083-4772
DOI: 10.24425/aep.2026.158389

Life cycle assessment of an experimental extensive green roof – a case study

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Keywords: LCA, environmental impact, carbon footprint, extensive green roof, sustainable building materials

Abstract: This study aimed to determine the environmental impact of extensive green roofs (EGRs) using a Life Cycle Assessment (LCA) based on an analysis of a 4 m² experimental EGR unit. A literature-based LCA was conducted, covering the first three life cycle stages, followed by a detailed LCA of these stages. The analysis was supplemented with carbon footprint calculations for the individual processes involved in constructing the experimental green roof unit (4 m²). The results showed that the production of green roof components, particularly synthetic materials such as polyvinyl chloride (PVC) and polypropylene, significantly contributes to environmental degradation. The carbon footprint of the 740.15 kg experimental green roof was 0.29 kg CO_2 equivalent per kilogram of green roof system (GRS). While this value is relatively low compared to, for example, selected food products, the environmental impact increases significantly when scaled to actual roof sizes, such as 100 m². Compared to similar studies, such as 150.99 kg CO_2 equivalent per m² for tropical green roofs, this study highlights the variability of environmental impacts depending on climate, materials, and design decisions. Although green roofs are intended to mimic natural ecosystems, current designs often rely on materials with high environmental impacts. Further research into sustainable alternatives and the inclusion of more CO_2-sequestering plant species are necessary to reduce their ecological footprint.

INTRODUCTION

Rapidly increasing global urbanization (United Nations, 2025) exerts growing pressure on existing green infrastructure (GI) in cities and significantly affects the quality of life for urban residents (Ashinze et al., 2024). The urban heat island (UHI) effect, resulting from rising temperatures of built-up and paved areas (Sierka & Pierzchała, 2022), leads to reduced vegetation cover and evapotranspiration, as well as increased anthropogenic heat production (Chen et al., 2022; Zhou et al., 2025). In response, the development of green infrastructure and the revitalization or improvement of its urban functions to prevent further degradation have become key priorities in numerous cities, particularly across European countries (Document 52013DC0249, EU 2013). Green infrastructure is recognized as a natural life-support system for regional environments and as a foundation of ecological security for the sustainable development of urban areas. Furthermore, GI improves the functioning of built environments by reconnecting people with nature, enhancing landscape aesthetics, and promoting social equity, among other benefits (Pauleit, 2019) as conceptualized by TEEB (2010) and MEA (2005). These benefits, commonly referred to as ecosystem services (Coutts & Hahn, 2015), play a critical role in improving the quality of life for urban populations (Çağlak et al., 2021).

Among the key components of urban green infrastructure (GI) are green roofs, a technology whose ecological and human-related benefits have been recognized since ancient times (Versini et al., 2020; Khalili et al. 2024). As rooftops account for approximately 20–25% of the total surface area in urban environments, they offer significant potential for achieving objectives such as reducing urban air temperatures through vegetation. Green roofs are therefore defined as horizontal living systems that help mitigate the growing environmental challenges of the modern world (Shafique et al., 2020).

The terms *green roof, living roof, ecological roof, vegetated roof or rooftop garden* generally refer to two main types of systems: extensive and intensive green roofs. Both types have historical precedents dating back to prehistoric times and were employed in various forms across many parts of Europe until the 19th century (Abass et al., 2020). The concept of green roofs in urban environments, aimed at delivering ecological benefits, underwent dynamic development in the late 20th century, with its modern resurgence originating in Germany (Köhler & Kaiser, 2021).

As awareness of the challenges posed by intensive urbanization and global environmental changes has increased, recognition of the benefits of horizontal green systems has grown across three key dimensions: environmental, social, and economic. In many European cities, green roofs are increasingly integrated into urban environmental planning. This trend is supported by European policy frameworks such as the EU Green Infrastructure Strategy (European Commission, 2013), the European Green Deal (European Commission, 2019) and the EU Biodiversity Strategy for 2030 (European Commission, 2020), which promote green infrastructure and nature-based solutions for sustainable urban development.

The results of review studies conducted in temperate climate regions indicate that green roofs are increasingly regarded as insulating systems that help reduce energy consumption and enhance retention of heat and rainwater at the local scale (Jamei et al., 2023).

Green roofs represent ecological building systems based on the principles of nature-based solutions (NbS), implemented in both new and existing buildings (Collier et al., 2021), where they perform various functions and deliver a wide range of ecosystem services in urban environments (Calheiros et al., 2021).

The growing interest in the development of green roofs within urban ecosystems, like any anthropogenic activity, entails interactions with the natural environment, for example, through the extraction of materials required for their construction (Santos et al., 2024). As a result, it has become essential to assess the environmental impacts associated with both the construction and functioning of green roofs (Brachet et al., 2019) throughout their entire life cycle, using life cycle assessment (LCA, Life Cycle Assessment, Life Cycle Analysis) (ISO 14040, 2006). Consequently, there has been a significant increase in the number of studies focusing on LCA in the field of green infrastructure (Fiorentin et al., 2024).

Moreover, increasing emphasis has been placed on the adoption of environmentally friendly materials to reinforce sustainable development and mitigate the effects of climate change worldwide. Green building aims to promote environmentally sustainable construction practices that contribute to energy conservation, emissions reduction, and the reuse and recycling of materials (Bungău et al. 2022; Deksissa et al., 2025).

Furthermore, life cycle assessment (LCA) is a key tool for the comparative evaluation of different roof types, including both extensive and intensive green roofs. Recent studies have applied LCA to individual layers and materials used in green roof construction, with the aim of identifying those with the lowest environmental impact (Scolaro et al., 2022), expressed, for example, in terms of carbon footprint (e.g., Kotsiris et al., 2019; Nadeshani et al., 2021). Such analyses are expected to support the identification of optimal and sustainable green roof designs in the future (Shahmohammad et al., 2022), particularly with regard to material selection.

In the pursuit of environmentally friendly solutions for the development of multifunctional green roofs, extensive scientific research is being conducted on so-called experimental roofs (Biela, 2023), often as part of studies carried out by students and doctoral candidates. The aim of the present study is threefold:

- To identify the components of the life cycle of a conventional extensive green roof.
- To analyze the first three stages of LCA of green roofs, within which the scientific experiment is conducted.
- To calculate the carbon footprint of the analyzed green roof system.

The anticipated outcome of this analysis is the identification of a functional unit for green roofs (Shafique et al., 2019), which may serve as a reference for estimating the carbon footprint of a full-scale green roof.

Extensive green roofs (EGRs) are a modern adaptation of the traditional “roof-garden” concept. They are characterized by shallower substrates compared to intensive roofs, requiring less maintenance and serving more specific ecological functions than intensive residential roofs or roof gardens (Todeschini & Fett – Netto, 2025). Often referred to as “eco-roofs,” extensive green roofs have shallow plant root systems and considerably lighter structures than intensive roofs, with weights ranging from 60 to 150 $kg \cdot m^{-2}$. The substrate depth typically varies from 5 to 15 cm (Kader et al., 2022).

In their simplest form, extensive green roofs consist of three fundamental layers: an insulating layer, a waterproofing membrane, and a substrate layer. Green roofs play a crucial role in managing stormwater and retaining heat within buildings (Jamei et al., 2023; Cook et al., 2025; Jayasooriya et al., 2025). The relatively shallow substrate layer in extensive roofs restricts plant selection to species with shallow root systems.

Regardless of type, green roofs, represent a class of technology that can be categorized as bioengineering or biomimicry. By mimicking natural ecosystems, they provide multiple ecosystem services and create shallow soil habitats that support associated biodiversity (Ndayambaje, et al. 2024).

With the growing need to develop innovative solutions to mitigate the negative impact of human activities on the natural environment, life cycle assessment (LCA) has emerged as a key analytical tool. LCA systematically evaluates the environmental aspects of a product, service, or process throughout its entire life cycle, allowing for a comprehensive assessment of its environmental impact (ISO 14040, 2006).

LCA supports decision-making processes related to the selection and optimization of available technological solutions (Michałowska, 2021). It can be applied to evaluate individual products, materials, or organizational practices, or complex production processes. Operating within the framework of International Organization for Standardization (ISO) management systems, LCA facilitates the assessment of environmental impacts across all five stages of the product life cycle:

1. Material extraction,
2. Transportation,
3. Production, assembly, construction,
4. Operation,
5. Disposal.

Throughout the LCA analysis, both the impacts on individual environmental components and entire ecosystems, as well as the consumption of various resources, are taken into account, providing a comprehensive evaluation of the environmental effects associated with a given product under study.

As defined by United Nations Environment Program (UNEP), "Life cycle assessment (LCA) is the process of evaluating the effects that a product has on the environment over the entire period of its life cycle …" (UNEP, 1999).

Research within the framework of LCA is carried out in four phases, each governed by specific guidelines outlined in the PE-EN ISO 14040:2006 standard. The PrPN-EN 14041 standard covers the first two phases: goal and scope definition, and life cycle inventory (LCI) analysis. The third phase, life cycle impact assessment (LCIA), which evaluates environmental impacts, is described in PrPN-EN ISO 14042 standard. The final phase, life cycle interpretation, is detailed in PrPN-EN ISO 14043.

Conducting an LCA and appropriately interpreting its results provides a better understanding of a product's composition and the environmental effects of its production stage (Ibn-Mohammed et al., 2024). Insights gained through this process can support the development of more economical, efficient, and environmentally sustainable product life cycle. Efforts to minimize the negative environmental impact of a green roof, from raw material extraction to disposal, are an important step toward sustainable development.

Materials and Methods

Preliminary Environmental Impact Analysis of a Green Roof

a. Scope of Analysis

In the preliminary analysis, individual components of a conventional extensive green roof, obtained from Polish manufacturers and contractors, were examined, and the carbon footprint of each process was calculated. This preliminary analysis enabled the application of the obtained results in the proper LCA analysis of the green roof.

Due to the experimental nature of the green roof studied, the preliminary analysis focused on the first three stages of the life cycle: material extraction, transportation, and construction.

The experimental roof serves as a research platform for vegetation introduced from areas with environmental conditions similar to those of extensive green roof, following the habitat template approach (Lundholm, 2018); in this case, the plants were sourced from hard coal mining waste heaps (known as "hałdy").

Plants transplanted from the heap were considered carbon neutral and assigned a zero carbon footprint. This assumption is based on the fact that the plants were not produced through cultivation process, and their acquisition did not involve emissions related to nursery production, fertilization, irrigation, or energy-intensive infrastructure. Furthermore, it was assumed that the biogenic carbon stored in plant biomass offset any potentially negligible emissions associated with the transplanting process.

Because the roof was constructed for experimental purposes rather than exploitation, only the construction stage was included in the LCA, while the operation and disposal stages were excluded from the analysis.

b. Analysis of Input and Output Flows About a Conventional Green Roof Construction

To conduct the preliminary analysis of components used in typical extensive green roofs, commercially available materials from manufacturers were examined. A green roof model was selected with a relatively complex structure, comprising the highest number of individual layers: vapor barrier, thermal

Table 1. Summary of input data (own elaboration: Z. Bedlińska)

Input data	
Electricity consumption	Electricity consumption during raw material extraction, material production, and transportation
Fuel consumption	Fuel consumption during raw material extraction, material production, and transportation
Water	Water used in production processes and for roof irrigation during drought conditions
Materials/raw materials required for roof construction	
Vapor barrier	Polyethylene (PE) vapor barrier foil
Thermal insulation	Styrofoam – expanded polystyrene (EPS 100)
Waterproofing	Synthetic rubber membrane made of ethylene propylene diene monomer (EPDM)
Protection mat	300 g protective geotextile made of polypropylene (PP) fibres
Drainage mat	2.5 cm drainage mat made of high-density polyethylene (HDPE)
Filter layer	Filter geotextile made of polypropylene (PP)
Substrate	Extensive substrate: 65% pumice, 30% compost, 5% zeolite; thickness: 6–8 cm
Vegetation	Bryophytes, Sedums, Grasses, Houseleeks, Succulents

Table 2. Summary of output data (own elaboration: Z. Bedlińska, E. Sierka)

Output data	
Main Product	Green roof
Emissions	Oxygen emission by plants through photosynthesis; emissions from production processes
Water	Water used in cooling and production processes
Green Waste	Weeds, withered plants

insulation, waterproofing, protective mat, drainage mat, filtration layer, substrate, and plant layer.

For the input data, materials and raw materials necessary for the construction of the roof were specified, along with estimated energy inputs, fuel consumption, and water usage needed for production or irrigation during dry periods (Table 1).

For the output data, the primary product – an extensive green roof – was defined, along with air emissions from the production processes, oxygen emissions from the plants, water used during production processes, and any potential green waste (Table 2).

LCA Phase and Carbon Footprint Calculation of Processes and Products

Environmental Impact Analysis of Green Roofs – Case Study Related to the Functional Unit of the Experimental Roof

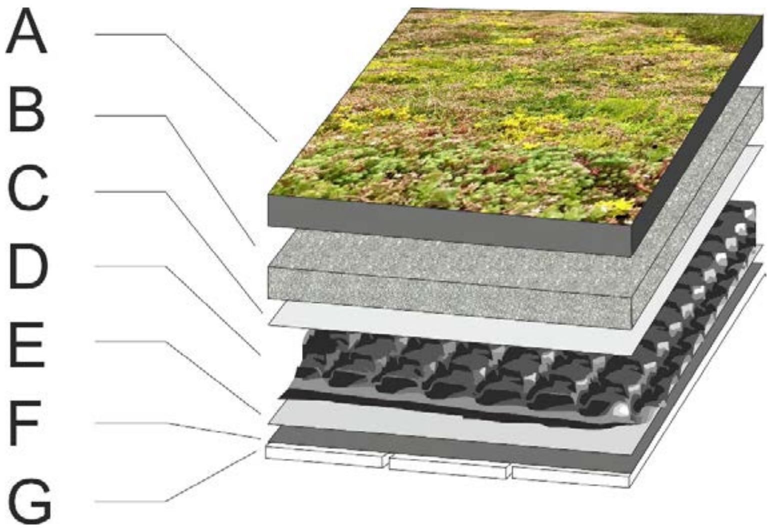
In the subsequent phase of the study, the environmental impact of the production processes for individual roof components (Table 3), as well as their transportation to the installation site (Table 4), was analyzed. The carbon footprint for each component was calculated based on the amount of product used (1 kg of each component). These calculations provided the basis for estimating the overall environmental impact of the green roof.

The carbon footprint data can be used to estimate the emissions associated with green roofs of varying sizes and to assess their broader environmental impact.

To perform these calculations, the open-source software OpenLCA (https://www.openlca.org/) was utilized. The "Environmental Footprint (PEF database)" from OpenCL Nexus (https://nexus.openlca.org/) was uploaded to the program. For comparison, the carbon footprint conversion

Table 3. Summary of the environmental impact of the production processes of individual green roof components and their carbon footprint (own elaboration: Z. Bedlińska, based on: openLCA – Environmental Footprint (PEF database) [26.07.2023]; https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023 [26.07.2023]; Androutsopoulos et al., 2019)

PROCESS	CARBON FOOTPRINT
PE/Plastic Film production	2,095 kg eq CO_2 [1 kg] (openLCA)/ 2,560 kg eq CO_2 [1 kg] (DESNZ & DEFRA, 2023) **2,328 kg eq CO_2 [1 kg]** Average value
EPDM Synthetic Rubber Production	**3,671 kg eq CO_2 [1 kg]** (openLCA)
Polystyrene including molding/forming	**3,764 kg eq CO_2 [1 kg]** (DESNZ & DEFRA, 2023)
Polypropylene (PP) fiber manufacturing including forming process	0,429 kg eq CO_2 [1 kg] (openLCA)/ 3,091 kg eq CO_2 [1 kg] (DESNZ & DEFRA, 2023) **1,76 kg eq CO_2 [1 kg]** Average value
HDPE including forming process	**3,256 kg eq CO_2 [1 kg]** (DESNZ & DEFRA, 2023)
Production of extensive substrate – coarse aggregate-based growing medium (pumice, compost, zeolite)	**0,205 kg eq CO_2 [1 kg]** (Androutsopoulos i in., 2019)



Legend:
A – vegetation layer;
B – volcanic substrate ZIDA, 15 cm;
C – filter geotextile by Optigrün;
D – drainage system mat Optigrün FKD 25;
E – absorbent and protective geotextile type RMS 300 by Optigrün;
F – waterproofing EPDM membrane “Resitrix SKW Full Bond”;
G – roof structure.

Fig. 1. Individual layers of the analyzed green roof (own elaboration: Magdalena Biela)

factors published by the UK Government for company reporting of greenhouse gas emissions were also used.

To estimate the carbon footprint of the substrate for the extensive green roof, previously published data were applied from (Kostris, et al. (2019) which reported carbon footprints specifically for substrates of extensive green roofs in the Greek Mediterranean climate.

Sensitivity analysis

Regardless of the LCA approach selected - conceptual, simplified, or detailed - sensitivity analysis is a key components of life cycle assessment (Fiorentin et al., 2024). To evaluate the influence of key assumptions and input data on carbon footprint calculations, a simplified sensitivity analysis was conducted. The analysis focused on selected life cycle inventory (LCI) parameters, while the life cycle impact assessment (LCIA) method and characterization factors were kept constant across all scenarios. A scenario-based approach implemented in OpenLCA was used, in which individual input parameters were modified while all remaining model assumptions were maintained constant.

The scope of the analysis included: (i) variation in substrate mass (±10%), representing the dominant component of the green roof system by volume, and (ii) the use of alternative emission factors for selected materials, for which averaged values had initially been assumed.

Environmental Impact Analysis of the Green Roof – Case Study concerning the Functional Unit of the Experimental Roof

For the purpose of this study, the functional unit was defined as 4 m² of an experimental extensive green roof, constructed specifically for research purposes. This unit serves as a reference for quantifying the environmental impact of the green roof system. Using the defined functional unit allows extrapolation of the results to larger green roofs and facilitates comparison of various green roof designs in terms of sustainability and carbon footprint.

Objective and Scope of the Case Study Analysis

This case study was conducted on five existing green roofs located in southern Poland (50°16’22’’N, 18°44’43’’E), constructed in 2022 using the Optigrün system (Fig. 1). Each experimental extensive green roof (EGR) covers an area of 4 m². The roofs were designed to support research on the use of plant species

Table 4. Summary of carbon footprints for different modes of transport (own elaboration: Z. Bedlińska, based on: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023 [26.02.2025])

PROCESS	CARBON FOOTPRINT
Transport of raw materials to the green roof installation site (van transport up to 1.3 t, petrol-powered)	**0,182 kg eq CO_2 [1 km]** (DESNZ & DEFRA, 2023)
Transport of raw materials to the green roof installation site (van transport up to 1.3 t, diesel-powered)	**0,142 kg eq CO_2 [1 km]** (DESNZ & DEFRA, 2023)
Transport of raw materials to the green roof installation site (transport by car, medium size, petrol-powered)	**0,178 kg eq CO_2 [1 km]** (DESNZ & DEFRA, 2023)
Transport of raw materials to the green roof installation site (transport by car, medium size, diesel-powered)	**0,167 kg eq CO_2 [1 km]** (DESNZ & DEFRA, 2023)

Table 5. Input data – analyzed experimental roof (own elaboration: Z. Bedlińska)

Input data	
Electricity Consumption	Electricity used during raw material extraction, material production, and transportation
Fuel Consumption	Fuel used during raw material extraction, material production, and transportation
Water	Water consumed during production processes and for irrigation of the roof during dry periods
Materials/raw materials required for roof construction	
Growing Medium	Pine wood boards (0.23 m³)
Waterproofing	EPDM Resitrix SKW Full Bond membrane – synthetic rubber (5.25 m²)
Protective Layer	Absorbent-protective geotextile, type RMS 300 (4 m²)
Drainage Mat	Drainage mat (4 m²) made of high-density polyethylene (HDPE)
Filtration Layer	Polypropylene (PP) filtration geotextile
Substrate	Extensive substrate – volcanic Zida (0.6 m³)
Plants	*Geranium robertianum, Calamagrostis epigejos, Lupinus polyphyllus, Echium vulgare*
Drainage Gutter	PVC gutter with a diameter of 10 cm (2.3 m)

from post-industrial areas in urban green infrastructure, with the aim of mitigating the effects of climate change.

Results from the preliminary analysis, based on the data presented in Table 3, were used in the main analysis to determine the carbon footprint and assess the environmental impact of existing or planned green roof projects.

Analysis of Input and Output Set

The experimental green roof, constructed for the experimental research purpose and for which carbon footprint values were determined, follows the typical layer arrangement of conventional green roof, with the exception of the thermal insulation layer. Unlike standard green roofs, this experimental roof is installed approximately 1.2 meters above ground level on a wooden platform rather than on a building. Each roof is equipped with a drainage system consisting of a gutter that directs water into containers for retention monitoring.

The experimental green roof consists of 6 layers: substrate, waterproofing, protective layer, drainage mat, filtration layer, and substrate with plants, along with a drainage gutter. For each 4 m² experimental green roof, the following materials were used:

- 0.23 m³ of pine wood for the construction of the research platform (G)
- 5.25 m² of EPDM Restrix SKW Full Bond membrane for waterproofing (F)
- 4 m² of absorbent-protective geotextile RMS 300 as the protective layer (E)
- 4 m² of FKD 25 drainage mat (D)
- 4 m² of geotextile filtration layer (C)
- 0.6 m³ (15 cm) of volcanic extensive substrate (B)
- 2.3 meters of 10 cm diameter PVC gutter for the drainage system

Life Cycle Assessment Phase

In this phase, the environmental impact of the experimental green roof was determined based on the results of the preliminary analysis. The carbon footprint of each component was calculated using the following formula:

product weight [kg] × carbon footprint of the process [kg CO_2 eq] = carbon footprint of the product [kg CO_2 eq]

Product weight [kg] = volume/area of the product × weight per m²/m³ of the product

The product weight was determined from its volume or area and the corresponding weight per cubic meter (m³) or per square meter (m²) for thin layers. Weight values for individual components were obtained from manufacturer specifications. Using the weight of 1 m²/m³ of each product and the amount used in roof construction, the total weight of each component was calculated proportionality.

Table 6. Output data – analyzed roof (own elaboration: Z. Bedlińska)

Output data	
Main Product	Green roof
Emissions	Oxygen emitted by plants during photosynthesis; emissions from production processes
Water	Water used in cooling and production processes
Green Waste	Weeds, withered plants

Table 7. Summary of the environmental impact of the production processes of individual products and their carbon footprint (own elaboration: Z. Bedlińska, based on: OpenLCA – Environmental Footprint (PEF database) [26.07.2023]; https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023 [26.07.2023]; Androutsopoulos et al., 2019)

PROCESS	CARBON FOOTPRINT
Substrate	
Wood production	**0,313 kg eq CO_2 [1 kg]** (DESNZ & DEFRA, 2023) **0,448 kg eq CO_2 [1 kg]** (openLCA) **0,381 kg eq CO_2 [1 kg]** Average value
To create the green roof, 0.23 m³ of material was used, weighing 126.5 kg	**48,2 kg eq CO_2**
Waterproofing	
EPDM synthetic rubber productionn	**3,671 kg eq CO_2 [1 kg]** (openLCA)
To construct the green roof, 5.25 m² of material was used, with a total weight of 6.9 kg	**25,33 kg eq CO_2**
Protective mat / Filter mat	
Polypropylene (PP) fiber production including forming process	**0,429 kg eq CO_2 [1 kg]** (openLCA) **3,091 kg eq CO_2 [1 kg]** (DESNZ & DEFRA, 2023) **1,76 kg eq CO_2 [1 kg]** Average value
To construct the green roof, 4 m² + 4 m² of material was used, with a total weight of 2.4 kg	**4,22 kg eq CO_2**
Drainage mat	
HDPE including forming process	**3,256 kg eq CO_2 [1 kg]** (DESNZ & DEFRA, 2023)
To construct the green roof, 4 m² of material was used, with a total weight of 3.2 kg	**10,42 kg eq CO_2**
Extensive substrate	
Production of extensive substrate	**0,205 kg eq CO_2 [1 kg]** (Androutsopoulos i in., 2019)
To construct the green roof, 0.6 m³ of material was used, weighing 600 kg	**123 kg eq CO_2**
Drainage gutter	
PVC production and forming	**3,399 kg eq CO_2 [1 kg]** (DESNZ & DEFRA, 2023)
The green roof was built using: 2.3 m, ø10 cm, weight: 1.15 kg	**3,91 kg eq CO_2**
Vegetation	
Collected plants from the hard coal mine spoil heap - reduction of the species populations *Geranium robertianum, Calamagrostis epigejos, Lupinus polyphyllus, Echium vulgare*	**0* kg eq CO_2 [1 km]** * The result is zero. Plants are not removed, but only transplanted to another location
Transport:	**0,178 kg eq CO_2 [1 km]** (DESNZ & DEFRA, 2023)
Route lenght: 50 km	**8,9 kg eq CO_2**
Total footprint of green roof:	**223,98 kg eq CO_2**

Table 8. Comparison of the experimental and typical roof in terms of their carbon footprint (own elaboration: Z. Bedlińska)

Layer	Typical green roof [4 m^2]	Experimental green roof [4 m^2]
Vapour barrier	1,257 kg eq CO_2	-
Thermal insulation	27,1 kg eq CO_2	-
Hydroinsulation	25,33 kg eq CO_2	25,33 kg eq CO_2
Protective mat	2,11 kg eq CO_2	2,11 kg eq CO_2
Drainage mat	10,42 kg eq CO_2	10,42 kg eq CO_2
Filtration layer	2,11 kg eq CO_2	2,11 kg eq CO_2
Substrate	123 kg eq CO_2	123 kg eq CO_2
Total:	**191,33 kg eq CO_2**	**162,97 kg eq CO_2**

Results

The carbon footprint of the 4 m^2 experimental green roof is 215.38 kg eq CO_2 [4 m^2]. Detailed results are provided in Table 7.

Sensitivity analysis

In Scenario I, a ±10% variation in substrate mass resulted in total carbon footprint range of 110.7 - 135.3 kg CO_2 eq, corresponding to a partial deviation of ±12.3 kg CO_2 eq. At the system level, this represented a ±5.7% change relative to the baseline scenario.

Scenario II revealed moderate variations in results, while the relative contribution of individual components to the total carbon footprint remained unchanged. For the wood production process, using alternative data sources resulted in total carbon footprint values ranging from 215.44 to 232.52 kg CO_2 eq, corresponding to a deviation of ±8.54 kg CO_2 eq from the baseline value of 223.98 kg CO_2 eq and a ±3.8% change at the system level.

For the process "polypropylene fiber production, including forming", alternative data sources yielded total carbon footprint values between 220.79 and 227.17 kg CO_2 eq, corresponding to a deviation of ±3.19 kg CO_2 eq from the baseline value of 223.98 kg CO_2 eq, resulting in a ±1.43% change in the total system carbon footprint.

Additionally, a sensitivity case was examined in which one of the averaged values was treated as the baseline. Assuming a baseline value of 215.44 kg CO_2 eq for wood production resulted in a difference of 17.08 kg CO_2 eq (approximately 8% of the baseline), while assuming a baseline of 223.79 kg CO_2 eq for polypropylene fiber production resulted in a difference of 6.39 kg CO_2 eq, corresponding to approximately 2.9% of the baseline.

Comparison of the Experimental Green Roof with a Conventional Green Roof

The experimental green roof (DE) differs from the conventional green roof (DC) mainly due to the absence of thermal insulation, such as polystyrene or Styrodur, and vapor barriers. Additionally, materials not commonly used in typical green roofs were included in its construction, such as gutters and wooden boards, which are part of the roof structure but are not strictly considered green roof components.

The carbon footprint of both roof types was compared for an area of 4 m^2. The total carbon footprint of the conventional green roof amounted to 191.33 kg CO_2 eq, whereas the experimental green roof exhibited a lower value of 162.97 kg CO_2 eq.

In the conventional green roof, the vapor barrier contributed 1.257 kg CO_2 eq, and the thermal insulation layer accounted for 27.1 kg CO_2 eq. These layers were absent in the experimental green roof, reducing its overall carbon footprint. In both roof systems, the waterproofing layer contributed 25.33 kg CO_2 eq, while the protective mat and filtration layer each accounted for 2.11 kg CO_2 eq. The drainage mat generated 10.42 kg CO_2 eq in both designs. The substrate represented the largest contribution to the total carbon footprint in both systems, at 123 kg CO_2 eq.

Overall, the removal of the vapor barrier and thermal insulation layers in the experimental green roof resulted in a reduction of 28.36 kg CO_2 eq compared with the conventional design, highlighting the potential of alternative construction solutions to reduce the environmental impact of green roof systems.

The comparison shows the carbon footprint of DE and DC, excluding the substrate and drainage system (gutter), as these elements were not part of the preliminary analysis. Plants were also excluded, as they are considered carbon-neutral within the scope of this assessment.

Summary and Discussion

One of the main limitations of the present study relates to the adopted system boundaries. Because the green roof was used for experimental research purposes, the assessment was restricted to the initial life cycle stages - material production, transportation, and installation. The use phase and end-of-life stage were deliberately excluded due to the experimental nature of the roof. The analyzed extensive green roof represents a research installation rather than a fully operational building roofs; its primary purpose is to enable controlled analysis of selected system components. Inclusion of the use phase and end-of-life stage would require additional assumptions regarding material durability, maintenance intensity, and dismantling and waste management, introducing substantial uncertainty for an experimental object. Nevertheless, the simplifications applied in the construction of the experimental green roof, such as the reduced number of layers and its installation on dedicated research platforms rather than on an actual building roof, do not affect the relative contribution of individual components to the total carbon footprint, which was the main focus of this study.

Uncertainty in the results is primarily associated with the use of secondary data from LCA databases and emission factor repositories, which reflect averaged production conditions and may not fully capture the specificity of local manufacturing processes, material composition, or regional differences. Simplified assumptions regarding material homogeneity and transport distances may also introduce additional uncertainty. Another source of uncertainty arises from the assumption that the vegetation used is carbon-neutral.

Despite these limitations, the study provides valuable insights into the carbon footprint of extensive green roofs and identifies key components responsible for the for the most significant environmental impacts. The results are particularly useful for comparative analyses and decision-making in the early stages of green roof design.

The life cycle assessment (LCA) of the experimental (DE) and conventional (DC) green roofs shows that both consist mainly of synthetic materials, including non-recyclable components such as PVC and polypropylene. Building such green roofs requires raw material extraction, energy-intensive manufacturing processes that release emissions, and transportation of finished components, all of which contribute to the overall carbon footprint.

Comparing the results with other studies remain challenging, primarily due to the lack of analogous units, e.g., kg eq CO_2·year^{-1} (Kotsiris et al., 2019). Nadeeshani, et al. (2021) reported a carbon footprint of 150.99 kg eq CO_2 $[m^2]$ for an extensive green roof in Sri Lanka, located in a tropical climate zone, which influenced the use of different materials such as sand, crushed rock, or paint. It also had significantly fewer layers of synthetic materials. The 4 m^2 DE roof analyzed here exhibits a slightly lower carbon footprint than DC, yet the values are comparable, indicating that even experimental roofs can generate substantial environmental impacts.

The total weight of the 4 m^2 experimental roof is 740.15 kg, corresponding to a carbon footprint of 0.29 kg eq CO_2 [1 kg]. While this is relatively low compared to certain food products (e.g., coffee – 17 kg eq CO_2 [1 kg], milk – 3 kg eq CO_2 [1 kg], beef – 60 kg eq CO_2 [1 kg] (Poore & Nemecek, 2018), the scale of green roofs is much larger. For instance, a 100 m^2 roof may weigh around 18.5 tons, significantly increasing its total environmental impact.

Sensitivity analysis confirmed that the LCA is most sensitive to substrate mass, with a 10% variation producing the largest change in total carbon footprint **(±5.7%). Using alternative databases for wood and polypropylene** showed moderate effects on the total carbon footprint (3.8% and 1.43%, respectively), indicating that precise determination of key raw material quantities is more critical to result reliability than the choice of data sources for structural components.

Although this study focuses on embodied emissions from production and installation, extensive green roofs can provide long-term environmental benefits through ecosystem services (Scolaro and Ghisi, 2022). Initial embodied emissions may be partially offset over the long-term operation of the roof, depending on factors such as climate, vegetation selection, maintenance, and lifespan. These aspects were not quantitatively assessed due to the experimental nature and limited system boundaries of the analyzed roof, representing important direction for further research.

Current green roof models offer significant room for improvement in minimizing environmental impacts during production. Many roofs are still dominated by synthetic “plastic” components, despite attempts to imitate in natural ecosystems. These findings underscore the need to offset negative environmental effects, for example, through carbon-sequestering plants, and to continue research into alternative construction methods and sustainable material choices.

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Ocena cyklu życia eksperymentalnego ekstensywnego zielonego dachu – studium przypadku

Streszczenie: Celem niniejszego badania było określenie wpływu na środowisko ekstensywnych zielonych dachów (EGR) przy użyciu oceny cyklu życia (LCA) na podstawie analizy eksperymentalnej jednostki EGR o powierzchni 4 m². Przeprowadzono analizę cyklu życia opartą na wytycznych i wartościach zawartych w literaturze, obejmującą pierwsze trzy etapy cyklu życia, a następnie szczegółową analizę cyklu życia tych etapów. Analizę uzupełniono o obliczenia śladu węglowego dla poszczególnych procesów związanych z budową eksperymentalnego zielonego dachu (4 m²). Wyniki wykazały, że produkcja elementów zielonego dachu w szczególności materiałów syntetycznych, takich jak polichlorek winylu (PCW) i polipropylen, znacząco przyczynia się do degradacji środowiska. Ślad węglowy eksperymentalnego zielonego dachu o masie 740,15 kg wyniósł 0,29 kg ekwiwalentu CO_2 na kilogram systemu zielonego dachu (GRS). Chociaż wartość ta jest stosunkowo niska w porównaniu na przykład z wybranymi produktami spożywczymi, wpływ na środowisko znacznie wzrasta w przypadku skalowania do rzeczywistych rozmiarów dachów, takich jak 100 m². W porównaniu z podobnymi badaniami, takimi jak 150,99 kg ekwiwalentu CO_2 na m² dla zielonych dachów tropikalnych, niniejsze badanie podkreśla zmienność wpływu na środowisko w zależności od klimatu, materiałów i decyzji projektowych. Chociaż zielone dachy mają naśladować naturalne ekosystemy, obecne projekty często opierają się na materiałach o dużym wpływie na środowisko. Aby zmniejszyć ich ślad ekologiczny, konieczne są dalsze badania nad zrównoważonymi alternatywami i wprowadzenie większej liczby gatunków roślin pochłaniających CO_2.