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Evaluation of photovoltaic-green and other roofing systems by means of ReCiPe and multiple life cycle–based environmental indicators

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ABSTRACT

The present study evaluates the environmental profile of a PV-green roof (PV panels over a soil/plant layer) and other roofing systems (PV-bitumen, PV-gravel, gravel, extensive green and intensive green). The analysis is based on multiple life-cycle impact assessment methodologies (ReCiPe, etc), several scenarios (for example with and without recycling) and it provides a deeper analysis as well as additional results to authors' previous investigation about PV-green roofs. The evaluation of the PV-green system (in terms of material manufacturing phase) shows that PV laminates (multi-Si) and steel components (joist, decking, balance of system) are responsible for the greatest part of the total footprint, based on GWP (global warming potential) and ReCiPe. Among the roofs which do not produce electricity, material manufacturing phase reveals that intensive green configuration has considerably higher impact in comparison with gravel and extensive green systems. Concerning PV roofs, PV-green configuration on a long-term basis (by considering material manufacturing, use phase, transportation and disposal), after a critical point, pays back its additional environmental impact (related with the "green layer") and it becomes more eco-friendly than the other two PV roofs. Certainly, this is due to the benefits (cooling effect of evapotranspiration, etc) of the soil/plant layer which result in PV output increase. The above mentioned critical point is determined by means of ReCiPe payback time and greenhouse-gas payback time. Several environmental indicators are calculated and presented along with results from the literature. A critical discussion is also provided.

1. Introduction

Photovoltaic (PV)-green roofs combine PVs with simple green roofs (with soil/plant layer) and they have been studied by the authors of the present work from experimental [1] as well as from theoretical point of view [2,3]. At this point it should be noted that for PV-green applications are more appropriate shallow-substrate green systems (extensive green roofs) and not deep-substrate green systems (intensive green roofs). This is related with factors such as the high height of the soil/plant layer of the intensive green configurations, their high weight as well as with aesthetic/building integration issues [1,3]. A critical analysis of factors affecting PV-green roof performance has been presented by Lamnatou and Chemisana [3].

A principal advantage of the plant/PV combination is the increase of PV output because of evapotranspiration cooling effect and in general because of plant/PV synergy, along with the other advantages which are also provided by the simple (without PVs) green roofs [3,4]. In the literature, there are few investigations about PV-green roofing systems: experimental studies [1,5–8], theoretical/modeling studies [2,6,9,10], critical review [3]. These investigations examine plant/PV interaction under several conditions (in terms of plant species, etc). For example for the Mediterranean climate summer conditions, two PV-green roofs (*Gazania rigens* and *Sedum clavatum*) and a PV-gravel roof (reference system) were examined [1]. The results for a sunny, five-day time period demonstrated an average increase of the maximum power output of the PV panels (ranging from 1.29% to 3.33% depending on the plant), verifying the positive interaction between PVs and plants [1].

By focusing on the techniques for the evaluation of the environmental impact of a system, Life Cycle Analysis (LCA) is a useful tool. However, in the literature there are few LCA studies about green roofs. In the following paragraphs, some of these studies are presented.

Saiz et al. [11] investigated an eight-story, residential building, in Madrid. By replacing a common flat roof with a green one (extensive), the environmental impact showed a reduction ranging

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from 1.0 to 5.3%. LCA was conducted for the whole building and by changing each roof option (assuming a 50-years building lifespan). A "bottom-up" approach was adopted. The stages of the life-cycle which were studied included material production and transportation, building operation and building maintenance (the construction phase and the end-of-life phase were not included) [11].

Kosareo and Ries [12] conducted a comparative LCA of intensive and extensive green roofing systems versus conventional roofs. The extensive green roof was based on an actual green roof project (retail store in Pittsburgh, PA, USA). The phases of fabrication, transportation, installation, operation, maintenance and disposal were considered. Ozone layer depletion, acidification, eutrophication, global warming and IMPACT 2002+ were adopted for the analysis. The results showed that the green roofs performed better than the control roof. In addition, the intensive green roof showed better performance than the extensive one. It should be noted that the goal of the LCA of [12] was to compare the environmental aspect and potential impact associated with constructing, maintaining and disposing of a roof (1115 m^2) and to determine the option with the lowest negative impact. The aim was the identification of the environmentally preferable choice between an extensive green roofing system, an intensive green roof and a conventional stone ballasted roof. Several aspects were considered in terms of the creation, operation and demolition of the roof area. Multiple environmental factors were monitored, such as thermal transmittance and water run-off. In addition, the energy consumption of the building, depending on the type of roof, was taken into account [12].

Rivela et al. [13] conducted an LCA, based on CML 2000, about green roofs of *Carex Testacea* and *Nassella tenuissima* (stipa) in Spain. The functional unit was "one square meter of a reverted flat roof with tile floating floor for private pedestrian use". The results revealed that the structural support had the highest contribution in all the studied impact categories, with the exception of "ozone layer depletion" category in which insulation showed 95% contribution.

Lamnatou and Chemisana [2] evaluated a PV-green roof along with other roof configurations: PV-gravel, green (extensive and intensive) and gravel, by means of different Life Cycle Impact Assessment (LCIA) methodologies: EI99, IMPACT 2002+ and Cumulative Energy Demand (CED). Stages of the phases of material manufacturing, material transportation, use and disposal were considered. The functional unit was the whole roofing system (300 m^2). The results revealed that material manufacturing is the most energy-demand phase for all the studied configurations. Emphasis was given on the PV-green roof and its comparison with the PV-gravel one, based on different scenarios. The results showed that although the PV-green configuration has an additional environmental impact in comparison with the PV-gravel one (because of the green-layer components), this additional impact on a log-term basis can be compensated.

Other studies in the field of green-roof LCA are those of: Hong et al. [14] (about life-cycle cost and life-cycle CO_2 analysis of green roofs in elementary schools with energy saving measures); Bianchini and Hewage [15] (about LCA of green-roof materials: it was demonstrated that the green-roof materials need to be replaced by more environmentally friendly products); Cerón-Palma et al. [16] (several green-space strategies for the building sector were examined); Bozorg Chenani et al. [17] (LCA of green-roof layers was conducted).

The literature review reveals that most of the LCA studies: 1) concern simple (without PV panels) green roofs, 2) focus on the benefits of the soil/plant layer for the building (e.g. energy savings during building use phase), 3) do not include multiple and newly-developed LCIA methodologies. In continuation to authors' previous LCA about PV-green and other roofing systems [2], the present article aims to provide new results by investigating the environmental performance of PV-green and other roofs by means of different LCIA methodologies, including newly-developed ones such as ReCiPe. An additional roofing system which includes PV modules over grey bitumen layer is introduced and compared with the other PV systems, strengthening the environmental benefits of the PV-green configuration. The analysis is based on multiple scenarios and several environmental indicators are evaluated, especially for the PV-green roof in comparison with other PV roofing systems. Critical points, after which the PV-green configuration becomes more eco-friendly than the other PV roofing systems, are identified. In this way, the present work along with authors' previous LCA study [2] provide a comprehensive profile of the environmental performance of the proposed PV-green configuration, based on multiple approaches.

2. Materials and methods

For the implementation of the LCA, according to ISO 14040:2006 [18] and ISO 14044:2006 [19], the following phases are adopted: 1) goal and scope definition, 2) life-cycle inventory, 3) life-cycle impact assessment and 4) interpretation.

2.1. Functional unit and system boundaries

The whole roofing system (300 m^2) is used as functional unit. The system boundaries include the roof in terms of material manufacturing phase. However, for the comparison of the PV roofs on a life-cycle basis, the boundaries except of material manufacturing include also use phase, transportation and disposal. Details about the components/materials and the adopted methods follow below.

2.2. System definition

2.2.1. Technical characteristics of the studied configurations

The roofing systems which are examined are: 1) gravel, 2) PV-gravel, 3) extensive green, 4) PV-green (extensive), 5) intensive green, 6) PV-bitumen (grey bitumen). The available roof area is assumed to be 300 m^2, considering a typical building with 30 m façade and 10 m width. The PV roofs refer to grid-connected PVs. The tilt angle of the PV modules, optimized in terms of the annual production for the case of Lleida (Catalonia, Spain), is 33°. Two rows of PVs are placed in parallel with around 5 m distance between the rows. Each row has 30 poly-crystalline Silicon (Si) PV modules. Each panel has the following characteristics: 230 W_p, $I_{mp} = 7.98$ A, $V_{mp} = 29.2$ V, 60 cells, 1.66 × 0.99 m^2 dimensions, electrical efficiency = 13.9%, weight = 18 kg (Source: [20]). Each row achieves 6.9 $kW_{p;}$ thereby, the total peak production of electricity is 13.8 kW_p. The BOS (balance of system) includes: aluminum frame, support structure (steel), copper and plastic materials for cables and contact boxes.

In terms of the roof components, all the roofing systems have structural support member (steel joist), decking (corrugated steel), insulation (polystyrene), underlayment (fiberboard) and asphalt adhesive. The above mentioned elements are common for all the roofs and they have the same amount of material, except for the intensive green roof where robust construction is needed and thereby, more steel is used for the support member. In addition, all the studied roofs include waterproofing membrane: 3-ply SBS (styrene-butadiene-styrene) for the non-green roofs and StressPly EUV (extreme ultraviolet) for the green roofs. Moreover, the green configurations have high-density polyethylene (HDPE) as drainage layer and filter fabric. Regarding the top layer, the green roofs have growing medium (height: 10 cm for the extensive and 100 cm for