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Photovoltaic-green roofs: a life cycle assessment approach with emphasis on warm months of Mediterranean climate

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ABSTRACT

The combination of Photovoltaics (PVs) with green roofs is a new tendency in the building sector and provides benefits such as PV output increase because of plant/PV interaction. The present study regards the evaluation of a PV-green roof along with other roof configurations: PV-gravel, green (extensive and intensive), gravel. The evaluation of the systems is based on Life Cycle Analysis by means of Eco-Indicator 99, IMPACT 2002+ and Cumulative Energy Demand methodologies. Stages of the phases of material manufacturing, material transportation, use/maintenance and disposal are considered and the results show that material manufacturing is the most energy-demand phase for all the studied roofs. The roofing systems are separated into PV roofs, non-PV roofs and the comparisons are conducted within each group. Emphasis is given on the PV-green configuration and its comparison with the PV-gravel one, based on different scenarios regarding PV output increase. The results reveal that although the PV-green system has an additional environmental impact in comparison with the PV-gravel one (because of its additional "green" components), this additional impact on a log-term basis can be compensated. Furthermore, the two PV roofs are compared with gasoil and those results also verify the benefits of the PV-green configuration regarding gasoil/cost savings and reduction of CO_2 emissions. In general, the study gives emphasis on warm months of Mediterranean climate since PV-green roofs have been proven beneficial under these climatic conditions. Finally, a discussion about critical factors in the field of PV-green systems provides a wider view of the studied issues.

1. Introduction

Towards green building design, the use of solar energy technologies such as Photovoltaic (PV) systems, in order to cover building energy needs, play an important role. PVs can be combined with roofing materials which are also used without PVs as the outermost layer of the roof: e.g. gravel (Chemisana and Lamnatou, 2014; Perez et al., 2012) or bitumen (Köhler et al., 2007). However, PVs can be also combined with green roofs (roofs covered with a soil/plant layer: Getter and Rowe, 2006). The combination of PVs with green roofs is a recent tendency (Chemisana and Lamnatou, 2014). A basic advantage of this combination is the improvement of PV efficiency. This is attributed to the cooling effect of the soil/plant layer because of Evapotranspiration (ET) and in general to the plant/PV interaction. However, in the literature there are few works about this specific type of roofing system: experimental works (Köhler et al., 2007; Hui and Chan, 2011; Perez et al., 2012; Nagengast et al., 2013; Chemisana and Lamnatou, 2014); theoretical/modeling studies (Witmer, 2010; Hui and Chan, 2011). These works verify the benefits of the plant/PV synergy showing a PV output increase ranging from 0.08 to 8.3% (details about these studies are presented in Section 2.6, along with their limitations).

Life Cycle Analysis (LCA) is a useful tool for the evaluation of the environmental impact of standard and green roofs (Saiz et al., 2006) in the building sector. In the literature there are several LCA studies e.g. about PVs (Sherwani et al., 2010); however, there are no works about LCA of PV-green roofs which could provide useful information for "green building" design as well as for academic/research purposes. It should be also noted that in the literature there are only a few studies about LCA of simple, green roof systems (without PVs). Following, representative works about LCA of simple, green roofs are presented revealing the benefits of the "green" layer e.g. for the building.

In the literature, there is a study about the comparative environmental life cycle assessment of intensive and extensive green roofs versus conventional roofing systems (Kosareo and Ries, 2007). The extensive green roof was from an actual 1115 m^2 green roof

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project, retail store in Pittsburgh, PA, USA. First, the characterization factors ozone layer depletion; acidification; eutrophication; global warming were adopted. Second, the Impact 2002+ method was used. Both methods agreed that the green roofs performed better than the control roof while the intensive green roof was better than the extensive one. The above mentioned work focused on the evaluation of the 'green roof' benefits for the building while the considered configurations did not include the use of PVs.

In the literature there is also another comparative LCA study about standard and green roofs (Saiz et al., 2006). An eight-story, residential building, in Madrid was studied. A standard gravel roof was compared with an extensive green roof (*Sedum* and other succulent plants) and a white roof. By replacing the common flat roof with a green one, the environmental impact reduced 1.0–5.3%. Summer cooling load was considerably reduced by over 6%. In that study emphasis was given on the 'green roof' benefits for the building and the considered roofing systems did not have PV modules.

There is also another LCA study (method: CML 2000) for green roofs (*Carex Testacea* and *Nassella tenuísima* (stipa)) in Spain: Cádiz, Valencia, Vigo, Madrid and Soria (Rivela et al., 2013). The structural support (concrete slab) had the largest contribution in all the impact categories, with the exception of the "ozone layer depletion" category, in which insulation (concrete tile with extruded polystyrene) had 95% contribution. Insulation and surface finish (plants/soil/felt layer) showed considerable impact. Thereby, in the same way with the two previous cited works that study focused on the 'green roof' benefits for the building while the considered roofs were without PVs.

Additional studies in the field of green roof LCA are following presented. Hong et al. (2012) studied extensive and intensive green roofs in combination with energy-saving strategies, for a variety of climatic conditions in Japan. It was proved that some scenarios, including green roofs combined with energy-saving techniques, were cost-effective. Another study is that of Bianchini and Hewage (2012) and it demonstrated that the current green roof materials need to be replaced by more environmentally friendly/sustainable products. Moreover, the study of Cerón-Palma et al. (2013) revealed that the "green-space" strategies, in the building sector, have the potential to reduce Greenhouse Gas (GHG) emissions due to CO_2 fixation. Also these investigations referred to the 'green roof' benefits from environmental point of view but they did not include configurations which combine green roofing systems with PVs.

From the above mentioned it can be seen that in the literature there are no LCA studies about PV-green roofs while there are only few LCA studies about simple, green roofs (without PVs). These works compared green with conventional roofing systems while some of these studies gave emphasis on the benefits of the soil/plant layer for the building. The results verified the advantages of the green roofs (e.g. for the energy savings of a building) in comparison with conventional roofs.

Thus, in the frame of the present work and based on experimental and theoretical works about PV-green roofs, a LCA study for several roof configurations (PV-green, PV-gravel, green (extensive and intensive), gravel) is performed in order to cover the gap which exists in the literature in the field of the assessment of the "PV-green" environmental impact. The Life Cycle Impact Assessment (LCIA) methods Ecoinvent 99 (EI99), IMPACT 2002+ and Cumulative Energy Demand (CED) are used. Emphasis is given on the PV-green roof and its comparison with the PV-gravel one. For a more realistic approach, different scenarios (based on literature references: Table 1) in terms of the PV output increase because of the plant/PV interaction are adopted. The main innovations of the present work are:

- The evaluation of the environmental performance of the considered PV-green roof and its comparison with the PV-gravel one: 1) by means of LCA; 2) by comparing gasoil use with the use of the PV-green and the PV-gravel system
- The examination of the effect plant/PV interaction, under different scenarios (including the case of Mediterranean climatic conditions), on the environmental performance of the PV-green roof

Table 1
a) References from the literature about PV-green roofs, b) adopted scenarios in terms of PV output increase due to the plant/PV interaction, based on the references.

a)

"PV-green" study	Type of study	Type of plants	Region	Time period	Increase of PV output	Additional comments
Hui and Chan (2011)	Experimental (large-scale)	*Sedum*	Hong Kong, China	Sunny summer day, 11-2 pm	4.3%	PV-green versus PV-bare roof
Perez et al. (2012)	Experimental (small-scale)	Varietal *Sedum*	New York, USA	June	2.56%[a]	PV-green versus PV-gravel
Chemisana and Lamnatou (2014)	Experimental (small-scale)	*Gazania rigens*, *Sedum clavatum*	Lleida, Catalonia, Spain	June–July	1.29% (*G. rigens*), 3.33% (*S. clavatum*)	PV-green versus PV-gravel
Nagengast et al. (2013)	Experimental (large-scale)	Mosses	Pittsburg, Pennsylvania, USA	July[b]	0.5%	PV-green versus PV-black
Witmer (2010)	Modeling		Different locations in USA		0.08–0.55%	
Hui and Chan (2011)	Modeling		Hong Kong, China	1 year	8.3%	PV-green versus PV roof mounted

b)

Scenario	Reference	PV output increase
1	Witmer (2010)	0.08%
2	Nagengast et al. (2013)	0.50%
3	Witmer (2010)	0.55%
4	Chemisana and Lamnatou (2014)	1.29%
5	Perez et al. (2012)	2.56%
6	Chemisana and Lamnatou (2014)	3.33%
7	Hui and Chan (2011)	4.30%
8	Hui and Chan (2011)	8.30%

[a] The collection of the data started May; this percentage (2.56%) regards June.
[b] That work refers to measurements over one-year. Under that cold climate, PV-green roof provided only 0.5% increase in power generation in July, whilst for all the year PV-black roof outperformed PV-green one by 0.5%.

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