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Photovoltaic-green roofs: An experimental evaluation of system performance

D. Chemisana *, Chr. Lamnatou

Applied Physics Section of the Environmental Science Department, University of Lleida, c/Pere Cabrera s/n, 25001 Lleida, Spain

HIGHLIGHTS

- PV-green roofs under summer Mediterranean climate have been experimentally studied.
- Two PV-green roofs (*Gazania*, *Sedum*) are compared with a PV-gravel, reference roof.
- Plant/PV synergy leads to PV electrical yield improvement for sunny, hot days.
- 1.29% and 3.33% increase in power was found for PV-gazania and PV-sedum respectively.
- Green systems reduced roof temperature; *Sedum* kept the roof cooler than *Gazania*.

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ABSTRACT

The research focused on the experimental evaluation of Photovoltaic (PV) – green roofs under Mediterranean climate summer conditions. Two autochthonous plants, *Gazania rigens* and *Sedum clavatum*, were selected for the PV-green systems while a PV-gravel configuration was used as the reference roof. The above mentioned roofing systems were developed and tested at the University of Lleida, in Spain. Research focused on electrical differential performances. In addition, thermal and irradiance analysis were also conducted. The results obtained for a sunny, five-day time period revealed an average increase of the maximum power output of the PVs (ranging from 1.29% to 3.33% depending on the plant), verifying the positive synergy between the PVs and the plants. Another positive effect of the plant/PV interaction was the fact that the PV-green systems showed considerably lower roof surface temperature in comparison with the PV-gravel configuration. Conclusively, the present work demonstrates the benefits of the PV-green roofs and fills the gap which exists in the literature in terms of the experimental evaluation of PV-green systems, especially under Mediterranean climatic conditions.

1. Introduction

The building sector is responsible for 40% of the energy consumption and 36% of the CO_2 emissions in the European Union. The results of studies showed that the implementation of energy systems which produce heat and electricity from renewable energy sources is one of the key actions towards the reduction of the energy dependence and CO_2 emissions, in the building sector [1]. In the field of renewable energy technologies, solar energy systems are important especially for countries with high solar radiation such as Spain. Among solar energy technologies, Photovoltaics (PVs) have been already applied in many sectors, including building sector, and they are a mature technology. Nevertheless, there is a potential for further development of the PV systems and this can be achieved for example by combining PVs with other ¨green¨ technologies such as green roofs. PV-green roofs are a new tendency and they can provide multiple advantages such as increase of PV output due to the plant/PV interaction and energy savings due to the soil/plant layer. Following, representative studies about PV efficiency, green roofs and PV-green roofs are presented.

PVs are a way to utilize the roof of a building with *in situ* production of electricity which can cover all or a part of the energy needs of a building. During the operational phase of this type of systems it is important the efficiency of the PV modules to be as high as possible. PV efficiency is affected by several factors such as cell material and temperature. PV efficiency decreases with increasing temperature and also the cells exhibit long-term degradation if the temperature exceeds a certain limit [2]. The open circuit voltage (V_{oc}) decreases significantly (about 2.3 mV/°C) with increasing temperature (reference temperature = 25 °C). This leads to a reduction of electrical efficiency (η) of around 0.4%/°C (β) for crystalline silicon solar cells as it is described in the following equation [3]:

* Corresponding author. Tel.: +34 973003711; fax: +34 973003575.
E-mail address: daniel.chemisana@macs.udl.cat (D. Chemisana).

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$$\eta(T) = \eta(25^{\circ})[1 - \beta(t - 25^{\circ})] \quad (1)$$

Thereby, cooling of the PV modules is important in order to keep the efficiency at high level [2].

On the other hand, green roofs are a totally different option for the utilization of the roof of a building and provide multiple benefits such as: air quality, temperature regulation, energy conservation, building envelope protection, increase of the longevity of the roofing membranes, economic and ecological benefits, and aesthetically more pleasing environment in which to work and live [4]. In the literature there are studies which verify the benefits of the green roofs in terms of building energy consumption. A recent study is that of Ascione et al. [5], which verifies the benefits of green roofs for the building sector. Several green roofs (in Europe) were studied including *Sedum* and gramineous (short and tall height), grass lawn. The results revealed that in warm climates green roofs are suitable for reducing the energy demand for space cooling: the annual reduction of the primary energy ranged between 1% and 11% for Tenerife, 0% and 11% for Sevilla and 2% and 8% for Rome.

From the above mentioned issues it can be seen that the combination of green roofs with PVs is an interesting option for the utilization of the roof of a building. This is because this specific roofing configuration combines the benefits of the soil/plant layer for the building, the *in situ* energy generation from the PVs and the possible synergetic effects between plants and PVs. However, in the literature there are only a few studies about PV-green roofs.

With respect to theoretical/modeling works, Scherba et al. [6] investigated the impact of roof reflectivity. The results revealed that the replacement of a black membrane roof by a PV-covered white or by a PV-covered green roof, led to reduction of the total sensible flux (approximately 50%). Another investigation is that of Hui and Chan [7]. The findings of a year-round building energy simulation (with EnergyPlus), for a low-rise commercial building, indicated that the PV-green roof generated 8.3% more electricity than the PV roof. It should be noted that the considered PV roof was roof-mounted with a few inches gap and the fact that there is no air circulation behind the module means that the difference in yield between this system and the PV-green one is expected to be higher. In addition, the above mentioned work also included an experimental part: measurements were taken in a rooftop garden in the University of Hong Kong on a sunny summer day from 11 am to 2 pm. Two PV panels were placed on a bare and a green roof. The PV-green system gave about 4.3% more electricity than the PV on bare roof (the PVs were not stacked on the roof) during the measurement period. In terms of the plant species, *Sedum* was considered. On the other hand, Sui and Munemoto [8] evaluated the performance of CO_2 Emission and Investment Value of a Green Roof Integrated Photovoltaic System (GRIPVS) by means of genetic algorithm. For that study, also *Sedum* was considered. Furthermore, Witmer and Brownson [9] developed a model for a PV-green roof, based on energy balance and microclimate effect. The above mentioned paper was based on a MSc thesis [10]. In the frame of that thesis, an energy balance model of a Green Roof Integrated Photovoltaic (GRIPV) system was developed and analyzed in a transient system simulation (by using a FORTRAN code in TRNSYS). Simulations in several locations in Unites States stated a small efficiency gain (0.08–0.55%) in power output. The author noted that further development of that model (in terms of experimentation and benchmarking) is necessary to refine the model for regional comparisons.

Regarding experimental works about PV-green roofs, Köhler et al. [11] investigated several PV-green roof configurations, dominated by *Sedum* species, in comparison with PV-bitumen ones, in Berlin. The results revealed that the green roofs had increased efficiency depending on the studied configuration. According to 5-year data, the ¨green roof¨ effect was estimated at an average 6% increase in yields. The authors noted that since there were many overlapping effects (reflection from other PVs, etc.), it would be desirable to continue that research and get results from other sites also in order to verify their findings. In addition, there is a study about CIGS (Cadmium–Indium–Gallium di-Selenide) PV cylinders combined with a *Sedum* green roof, based on the analysis of Penn Statés 2009 ¨Natural Fusion¨ home which was designed for the 2009 Solar Decathlon. Gains in performance were outlined; however, there are no specific results available in the literature about the increase of the PV efficiency due to the plant/PV interaction [12]. That work is related with Ref. [13]. In the literature there is also a study conducted in Pittsburg (Pennsylvania). Measurements over a one-year study period (1-7-2011 to 30-6-2012), from a large field project in Pittsburgh, were used to determine the differences in power output from green and black roofs as well as to derive two regression functions for back-surface panel temperature and PV output. The results showed that a PV-green roof, under those climatic conditions (73% of ambient temperatures below 25 °C and 90% of solar irradiance values lower than 800 W/m^2), can provide only a small positive impact of 0.5% in power generation in July, whilst for all the year the PV-black roof outperformed the PV-green one by 0.5%. They remarked that for days achieving temperatures higher than 25 °C and/or irradiances higher than 800 W/m^2 PV-green roof started to outperform the PV-black configuration. It should be noted that moss was adopted for that PV-green system [14]. Another experimental study is that of Perez et al. [15]. In the frame of that study, multiple small-scale roof systems: gravel, green, PV-gravel and PV-green, over small model houses were evaluated, in New York. Regarding the plants, varietal *Sedum* species were adopted. Surface temperature variability on the gravel house was 10.69% higher than on the ¨PV-green¨ house. Mean internal and surface temperatures were 5.1% and 1.73% higher on the gravel roof than on the ¨PV-green¨ one, respectively, while PV performance saw a 2.56% increase in June.

Thus, based on the PV-green studies which are available in the literature, the ¨symbiosis¨ of the PVs with the plants can lead to PV performance enhancement, depending on factors such as the type of the plant and the weather conditions of a certain region. However, it can be seen that there is a gap in the literature in terms of the experimental evaluation of PV-green systems in general and in particular dealing with their electrical performance. The present work aims to fill this gap by investigating the experimental behavior of two PV-green roofs and their comparison with a reference, PV-gravel roof, under the Mediterranean climatic conditions of Spain. More specifically, the research is addressed to determine performances, and to contrast them with the literature, under the hot summer days where the highest efficiency drop arises because of the high temperatures occurred and since this type of days are characteristic of Mediterranean climate regions. In addition, the present study provides data about the experimental behavior of PV-green roofs under Mediterranean climatic conditions, filling another gap of the literature, since the studies which are currently available regard other climate types. In this sense, autochthonous and perfectly adapted to Mediterranean climate plants with aptitudes for positive interaction with the building and the PVs were selected. Apart of the electrical performance, thermal and irradiance characterizations were conducted to analyze the effect of the PV/roofing system on the soil/gravel at the roof surface and the reflection/albedo affectation in the irradiance at the module plane.

2. Selection of the appropriate plant species

For the selection of appropriate plant species for PV-green roof systems, multiple criteria should be taken into account e.g. suit-