

Performance of Green Roof Integrated Solar Photovoltaic System

M F Chow, L. Ling, W. L. Tan, V Arenanda, K. A. A. Aziz, Y. M. Yusof



Abstract: Green roofs and solar photovoltaics are green technologies that developed to meet the sustainable and low carbon emission targets by the ways of effective stormwater management and renewable energy generation. Previous studies have proved that the cooling effects from the evapotranspiration process in green roofs can keep the photovoltaics (PV) near the best operational temperature, while PV panel can provide the shading benefit to the green roof's vegetation. The paper aims to synthesize the influential factors, including solar PV and green roof designs on solar power output efficiency. This review identifies the research gaps in the previous studies of green roof integrated solar PV system and highlights the desirable characteristic for each component. This review also suggests a guideline to construct practical green roofs integrated solar PV system.

Keywords: Review, Rooftop and Solar Photovoltaic

I. INTRODUCTION

Urbanization process is undergoing rapidly in many developing countries especially Southeast Asia countries. The urban development has increased the stormwater runoff, pollutant build-up, urban ambient temperature and other related environmental problems (Jacobson *et al.*, 2012; Chow *et al.*, 2013; Chow *et al.*, 2015; Haris *et al.*, 2016; Chow and Yusop, 2019). Green roofs or vegetative roofs, are one of the sustainable building technologies that can address many environmental challenges resulting from urbanization (Solcerova *et al.*, 2017; Chow and Bakar, 2019).

Green roof can be categorized as intensive and extensive green roofs, depending on the soil depth, plant species and components. Green roofs have been widely used in the sustainable development of urban city in the past few decades.

Green roof (GR) reduces the building energy consumption (Jaffal *et al.*, 2012; La Roche and Berardi, 2014;), decrease ambient and surface temperatures (Chemisana and Lamnatou, 2014; MacIvor *et al.*, 2016; Oberndorfer *et al.*, 2007; Peng and Jim, 2013), improve air quality (Li *et al.*, 2010), reduce storm water runoff (Beattie and Jarrett, 2009; MacIvor *et al.*, 2016; Mentens *et al.*, 2006; Chow *et al.*, 2017; Chow *et al.*, 2018), increase roof lifespan (Chemisana and Lamnatou, 2014), improve aesthetics (Jungels *et al.*, 2013) and provide space for habitat (Garrison *et al.*, 2012). By providing cooling benefits, a green roof can serve to counterbalance the urban heat island (UHI) effect that is generated by the concrete surface and waste heat generated by building, industrial activity, transportation and their energy use (Santamouris, 2014).

Solar panels or solar photovoltaics (PV) are another technology that commonly installed on urban rooftops. As urbanization continues to rise, energy demands and associated greenhouse gas emissions and pollution also increase these necessitating alternative low-carbon energy solutions. In view of that, integrating both PV and green roof system is gaining more interest as a practical solution for optimizing both systems' performances as shown in Figure 1. Previous research demonstrated that combining green roof with PV panels can provide multiple benefits which including increasing the PV energy generation efficiency, lowering down the operating temperature of PV panel surface by evaporative cooling effect of plants, effective stormwater management and enhancing the urban aesthetic values (Köhler *et al.*, 2007; Singh *et al.*, 2008; Hui and Chan, 2011; Meral and Diner, 2011; Perez *et al.*, 2012; Breuning *et al.*, 2013; Chemisana and Lamnatou, 2014; Hoffmann and Koehl, 2014; Ogaili and Sailor, 2016;). To achieve a better understanding on the benefits, cost-effectiveness, and environmental impacts of a green roof integrated solar PV system, it is necessary to conduct a study on the practical design of this system. Thus, the objective of this review paper is to synthesize the effects of the influential factors, including solar PV and green roof designs on solar power output efficiency. This review identifies the research gaps in the green roof integrated solar photovoltaics system and highlights the desirable characteristic for each component. The review also suggests a guideline to construct practical green roofs integrated solar photovoltaics system.

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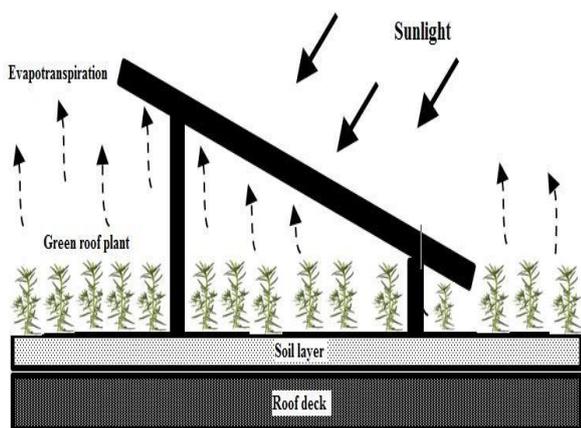


Fig. 1 Integrated green roof-solar solar photovoltaic (PV) system

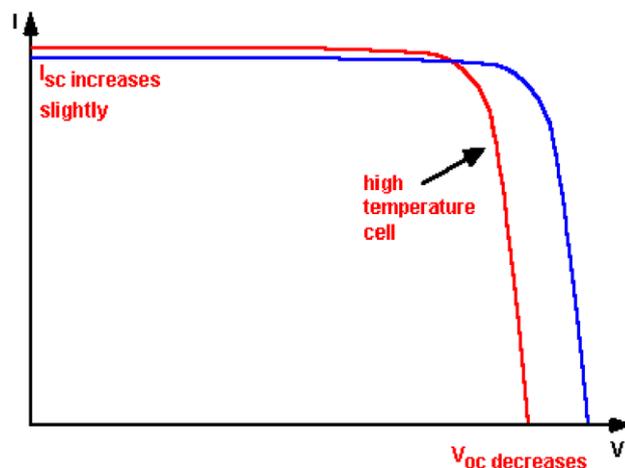


Fig. 2 I-V curve shows how the voltage decreases with increasing the temperature

Effects of temperature on solar power efficiency

Solar photovoltaic (PV) system is an assemble of series solar cells that made of silicon semiconductors with encapsulation protection from the humidity and dust at surrounding environment. The characteristics of open and short circuit voltage (V_{oc}) and current influence the performance of these semiconductor based solar cells. Optical losses and cell temperature are the main two factors that lead to the reduction of solar cell efficiency. The increase of cell temperature is mainly due to the solar radiance and heat. Generally, solar cell would absorb the high-energy photon but only small part of those solar lights are converted into electricity which depends mostly on the efficiency of solar cell. Subsequently, more heats produced from the excess energy of that incident light. When the cell temperature rises, the band gap becomes occupied with energy and thus reducing the generated maximum solar energy. While the rise of irradiance may slightly increase the generated PV power, however, the open circuit voltage will decrease remarkably as well. Hence, the depletion of open circuit voltage will affect the solar cell’s total performance in term of maximum energy output and efficiency (Singh *et al.*, 2008).

Figure. 2 shows the I-V curve on the reduction of voltage with increasing cell temperature. Generally, irradiance of 1000 Wm^{-2} and PV panel temperature of $25 \text{ }^{\circ}\text{C}$ are the standard reference points for assessment of PV products and devices. High irradiances are normally come with higher temperature in the field application, which may significantly lower down the voltage and efficiencies of the solar cell. The most critical loss factor in a PV performance testing is laying on the solar cell temperature at a given irradiance (Dubey *et al.*, 2013; Dupre *et al.*, 2015; Fesharaki *et al.*, 2011). The ambient temperature that influenced by the surrounding environmental conditions, will determine the operating temperature of the solar cell. More heat intake would be experienced by the PV system that installed on the flat concrete roof due to its low albedo coefficient (< 0.1). Low albedo material will radiate high energy flux to the PV panel and local environment.

Evaporative cooling effects by green roof system

In a review of simulations and experimental studies on the evaporative cooling potential of green roof, Santamouris (2014) observed that if green roof is being used in a city scale, it may reduce the ambient temperature by 0.3°C to 3°C . Peng and Jim (2013) modelled the impacts of community-scale green roofs in Hong Kong and estimated that extensive green roof reduced pedestrian-level temperatures and rooftop level temperatures by up to 0.7°C and 0.9°C , respectively, while intensive green roof reduced temperatures by up to 1.7°C and 2.1°C , respectively. In addition to vegetation type, Peng and Jim (2013) suggested that a potential relationship exists between increased cooling effects and low rise and density areas with aligned wind direction. A model for the Baltimore-Washington metropolitan area presented by Li *et al.* (2014) indicated that reduction of surface temperatures by 0.5°C may require 90% of the roof area to be covered by a green roof but if a white roof is used, 95% of the roof area need to be covered. The effect of ambient air temperature above green roof modules was studied by researchers at the University of Toronto’s Green Roof Innovation Testing (GRIT) Laboratory (MacIvor *et al.*, 2016). The authors observed that the cooling effects of a green roof (GR) depend on the GR design characteristics including soil type, vegetation type, and irrigation regime. MacIvor *et al.* (2016) noted that green roof modules with sedum, compost-based growing media, and supplemental irrigation, provide more cooling effects (1.5°C more) than roofs with grasses, wildflowers, mineral-based media, and no irrigation. Additionally, an average temperature reduction of 2°C was observed at a 6” height from the GR surface. Bass *et al.* (2002) studied the degree to which GR could reduce the UHI effect within the City of Toronto. Their model demonstrated that when GR in urban areas received sufficient irrigation to drive the evapotranspiration process, the surface temperatures in the city could be reduced by $1\text{-}2^{\circ}\text{C}$ at noon. Another model for the City of Toronto showed that by adding irrigated green roof to 50% of the available roof space in Toronto, the citywide air temperature can be decreased by 2°C and non-

Irrigated GRs could reduce city temperatures by 0.8°C (Liu and Bass, 2005). Similarly, Oberndorfer *et al.* (2007) found that models of transforming 50% of roofs to GRs in Toronto could result in an annual temperature reduction of 2°C throughout the city. The summary of evaporative cooling effects by green roof is shown in Table 1.

Table. 1 Summary of evaporative cooling effect by green roof

No	Study	Finding
1.	Santamouris, M. (2014).	Reduction of surrounding temperature by 0.3°C to 3°C by green roof.
2.	Chemisana, D., & Lamnatou, C. (2014).	The soil temperature of green roof was lower than that of the black roof and white roof surfaces.
3.	Peng, L. L. H., & Jim, C. Y. (2013).	Extensive and intensive green roofs are able to reduce the temperatures of pedestrian-level temperatures and rooftop level by up to 0.7°C and 0.9°C and 1.7°C and 2.1°C, respectively.
4.	Ogaili, H., & Sailor, D. (2016).	PV-green roof has lower mean temperature than that of the black and white roofs.
5.	Hui, S. C. M., & Chan, S. C. (2011).	The temperature on PV-green roof was cooler up to 11°C than that of PV-bare roof.

Green roof integrated solar photovoltaic studies

Several researchers from different part of the world have carried out the studies of integrating green roof and PV systems. Scherba *et al.* (2011) in Portland Oregon, USA had found that a PV-green roof can reduce approximately 50% of total sensible flux compared to black membrane roof. Hui and Chan (2011) carried out their building energy simulation study in Hong Kong found that PV-green roofs can generate 8.3% more power output than the PV-conventional roof. It is noted that small gap between the roof and PV panel system may block the air circulation which subsequently causing the heat trapped underneath of the panels. Other than that, Hui and Chan (2011) also conducted an experimental study on a sunny day from 11:00 am to 2:00 pm to determine the differences between PV-green roof and PV-bare roof systems. The experimental study revealed that the temperature above the PV-green roof

was cooler up to 11°C and 4.3% more electricity generation than PV-bare roof. Other than that, the PV panel had reduced the surface temperature of green roof by 5°C compared to control green roof.

Köhler *et al.* (2007) in Germany had investigated several PV-green roof configurations and found that integrating PV panels with green roofs can improve the PV system’s efficiency by an average of 6% based on his five years’ experimental data . This result may depend on several factors which including different configurations of tracking systems, inverters, and tilt angles. Other than that, the studies conducted by Köhler *et al.* (2007) have proved that PV-green roof system can reduce 33 Kg/year of CO₂ emission. Another experimental study by Singh *et al.* (2008) in Pittsburg, Pennsylvania, USA had found that PV and green roof system generated more power output than PV and black roof system if the surrounding temperature and irradiance are higher than 25°C and 800 W/m², respectively. Seasonally, the PVs-green roof produced 0.5% more electricity energy in summer, whereas the PVs-black roof produced more electricity in winter.

Perez *et al.* (2012) in New York, USA found that the PV and green roof integration system generated 2.56% more electricity than that of the PV and gravel roof. It was observed that higher gap between PV panel and green roof in this study may allow more air circulation under the PV panel and thus reduced the temperature of PV modules. Chemisana and Lamnatou (2014) performed their study at the University of Lleida, in Spain. Their experimental results over two months monitoring periods revealed that the mean maximum power generations of 3.33% and 1.29% were observed for the PV systems with sedum and gasania, respectively. Lower temperature of the PV panel of 4.2% in average was observed above the gazania green roof compared to that above the gravel roof. Sedum has been found that it can enhance 1.43% more irradiance than the gazania plant.

Ogaili *et al.* [2016] revealed that the PV-green roof integration system has higher power output of 1.16% and 0.75% than the PV systems above the black and white roofs at 18 cm height, respectively. Meanwhile, the PV-green roof produced 1% and 0.68% more electricity than the PV systems above the black and white roofs at 24 cm height, respectively. The PV-green roof also recorded lower mean temperatures than that of the black and white roofs, respectively. The previous studies have demonstrated the benefits of PV-green roof integration system. The summary of the performance of PV-green roof integrated system is shown in Table 2.

Table. 2 Summary of performance of green roof integrated solar photovoltaic system

No.	Study	Finding
1.	Hui, S. C. M., & Chan, S. C. (2011).	8.3% more electricity generated by PV-green roof than the conventional PV panel at a low-rise commercial building.
2.	Köhler, M., Wiartalla, W., & Feige, R. (2007).	The PV- green roof integration system increases the electricity energy by an average of 6%.
3.	Perez, M. J. R., Wight, N. T., Fthenakis, V. M., & Ho, C. (2012).	PV-green roof has 2.56% higher power output than that of PV system above gravel roof.
4.	Singh, P., Singh, S., Lal, M., & Husain, M. (2008).	The PVs-green roof generated 0.5% more power output than PVs-black roof.

Benefits, challenges and recommendations

This review paper has highlighted the benefits of integrated green roof-solar photovoltaics system on temperature reduction and improvement on solar PV power generation efficiency. The benefits of this integration system depend on weather conditions and designs of green roof system including plant species, soil type/depth, and irrigation. This review paper also suggests some design guidelines to construct practical green roofs integrated solar PV system for improving the performance of both systems. It is recommended to adopt sedum species in the green roof system in order to enhance the optimum energy output of PV panel. The PV-green roof system is also recommended to be installed at lower height from the green roof ground level.

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