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Photovoltaic Energy Variations Due to Roofing Choice

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Abstract

Roofs comprise 20-25% of the total urban surface area and with different roofing technologies and photovoltaic, present an opportunity for sustainable building designs. The operation temperature of photovoltaic (PV) modules has a significant impact on the conversion efficiency and output energy of the PV system. This research investigated the thermal interactions between the building envelope and PV panels by examining the PV panel temperature differences for those installed over a green roof (PV-green) and those installed over a black roof (PV-black). A LEED platinum certified educational building with roof mounted PV panels was used as a case study for the experimental phase of the study. PV panels over the green roof consistently recorded lower temperatures than PV panels over the black roof. Therefore, the PV panels over the green roof had more energy output compared to the PV panels over the black roof.

Keywords: Photovoltaic; Energy; Roofing Types; Roofing Technologies

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1. Introduction

One challenge humans face in the 21st century is tackling the energy problem. While energy consumption increases in all end-use demand sectors, energy use in the buildings sector is projected to grow the fastest, with an average annual growth rate of 1.6 percent per year. The building sector worldwide accounts for more than one-fifth of the total worldwide energy consumption and has an expected increase of 38% from 2010 to 2040 [1]. Buildings in the United States consumed 41% of primary energy in the country and 7% of total primary energy worldwide [2]. The

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challenge is that three-fourth of the world's energy infrastructure heavily depends on fossil fuels. The problems with fossil fuels are: they are a major producer of greenhouse gases and humans deplete them faster than they are generated through the photosynthetic process in nature. Although the worldwide fuels used to generate electricity have changed over the last decades, coal and natural gas accounted for more than 60% of the overall worldwide electricity production in 2010 [3].

Solar energy is a promising source of energy that has received greater public attention in the last decade. In 1999, the total worldwide installed photovoltaic (PV) power reached 1 GW and in 2013 it surpassed 138 GW of installed power [1]. In 2014, around 40 GW of PV capacity was added to reach a global total of about 177 GW [4]. Over the past three years, around 60% of all the worldwide PV capacity was added. Germany took the lead since the beginning of the new millennium with their progressive renewable energy policy, leading to a large national solar market with 43% and 38% of the PV system installed worldwide in 2010 and 2014 respectively [4, 5]. The top two markets in 2014 were China and Japan, with new additions of 10.6 and 9.7 GW respectively added to the total capacity [4]. The United States installed PV capacity increased by 54% in 2010 [6] by installing close to 900 MW of new PV electricity generation capacity to reach a cumulative PV capacity of 2.5 GW. The PV projects with Power Purchase Agreements which was already under contract and to be completed by 2014 has a total capacity of 6.1 GW and 10.5 GW of projects have already been publicly announced [7].

According to the National Renewable Energy Laboratory (NREL), the rooftop mounted systems accounted for 74% of the installed PV generation capacity in the U.S. during 2008 [8]. The two most common types of PV modules are: crystalline silicon with a market share of 85-90%, and thin file with a market share 10-15% [5]. The conversion efficiency of the crystalline silicon is with a range from 20% up to 27% while the thin film has a conversion efficiency of 13-19% [9, 10]. The conversion efficiency of PV module is tested in laboratories under controlled environments using a specific procedure called Standard Test Conditions (STC). The conversion efficiency of the PV in reality is lower than efficiency measured under the STC due to several factors such as resistances in the electrical circuit, irradiance level, dirt and dust, shade, and air speed and temperature [11].

The operation temperature of PV modules has a significant impact on the conversion efficiency and energy output and PV manufacturers publish temperature coefficients relating losses in efficiency for each degree the temperature fluctuates from the base of 25°C (77°F). Nordman and Clavadetscher found that with an 8°C (14°F) temperature increase over 20°C (68°F), PV panels had 1.7 to 5 % decrease in power output [6]. Another study found that the PV module efficiency decreases from 12.7 % conversion efficiency at a surface temperature of 22°C (71°F) to 9 % conversion efficiency at surface temperature of 60°C (140°F) [11]. The reduction of the PV surface temperature can be achieved by cooling the module and reducing the heat stored inside the PV cells during operation. It becomes a common knowledge in the industry that PV temperature has an impact on the conversion efficiency and an effective way of improving efficiency of a PV module is by reducing the operating temperature.

2. Literature Review

The growing interest of solar technology promotes more accurate estimations of the PV output when integrating it in buildings. The operation temperature of the PV panel can be influenced significantly by the wind speed and direction [6, 12, 13]. The air velocity behind PV panels increased in proportion to the size of the air gap [14]. Gun (2009) found a reduction of approximately 14°C (25.2°F) of the maximum PV temperature and up to 6% increase of the electricity output for PV with proper ventilation in comparison with non-ventilated. Another study shows that with an appropriate air-gap width behind a PV panel, the mean temperature of the panel can be lowered by 30°C (54°F), allowing for a significant increase in its electricity output [14-16].

Furthermore, there is a thermal interaction between the PV panels and surrounding surfaces. The selection of roofing materials is important for buildings with integrated PV systems. The interaction between roofing materials and PV panels has not been widely studied, and few works have compared the operation temperatures and the power output of PV panels in relation to roof-surface temperature.

In the literature there are a few works about the impact of green roof to PV operation temperature and efficiency. These works verify the benefits of the plant/PV synergy, showing a PV output increase ranging from 0.5 to 8.3% [17-21]. A field experiment in Germany compared the average efficiency of PV panels over green roof assemblies to the average of PV panels over bitumen roof systems. The results show that a green roof increased PVs efficiency by an average of 6% yields. The monthly average of the PV over green roof systems outperformed PV over bitumen roof assemblies monthly by -4% to 3% with a yearly average of 1.5%. The green roof surface temperatures were lower than surface temperatures of black roof recording 22°C (71°F) and 38°C (100°F) respectively [6, 17].

A one-day field experiment in Hong Kong compared the performance of two PV panels over a conventional and a green roof. The green roof's surface temperature was 5-11°C (9-19°F) cooler than the conventional roof and the PV over the green roof generated 4.3 % more electricity [21]. Nagengast et al. conducted an experiment in Pittsburg, PA to investigate the impact of the ambient temperature to the PV output by comparing the performance of PV array over green and black roofs. The experiment results show that power generated from PVs over a green roof was about 0.5% more than PVs over a black roof in July only, while for the rest of the year, the PVs over a black roof outperform the output of PV on a green roof [6, 19]. A field experiment during two hot months in Spain investigated the behaviour of a PV over two different green roofs (sedum and gazania) with a PV over a gravel roof. The study reveals that PV over gazania and sedum roofs generated more electricity of 1.29% and 3.33%, respectively, in comparison with the PV over a gravel roof. Also, PV module placed over sedum achieved a higher increase of power of 2.24%, than the one placed over gazania. In terms of the roof surface temperature, over five-day period, gazania green roof recorded an average daily of 17.8 %lower than the gravel roof and the sedum reported an average daily of 26.1% lower [20].

Previous literatures studies the thermal interaction between PV panels and roofing types with some limitations. The limitation varies from experiment durations and instillation differences. The experiment in Germany compare the performance of two groups of PV panels but the number of PV panels, type, and inverters were different. The study in Hong Kong run the experiment for several hours only. Nagengast et al. conducted the experiment for a longer period of time with the same insulation, but the ambient temperature in Pittsburg, PA was cooler than the 25°C (77°F) for most of the year hours and the result was not significant. This study compare the performance of the same PV panel number, type, tilt, height, and inverter over two roofing types during summer days.

3. Research Design and Procedure

Figure 1: Center for Design Research

Figure 2: Center for Design Research (CDR) Roof

For the experimental phase of the research, an existing building on the University of Kansas (KU)'s west campus will be used to conduct the first phase of the study, which is the Centre for Design Research (CDR). It was designed and built by the Department of Architecture's Studio 804 and certified as a LEED Platinum building in 2013. It was the first in Lawrence and at KU to receive the Platinum designation. The CDR has PV panels accompanied with a white and a green roof. The PV system is loaded with monitoring system that reports the energy production from solar panels to an online database, however, the existing monitoring system reports the energy output for the entire system. The temperature coefficient listed in the manufacturing specifications sheet for the CDR's PV panels is -4.5*10^{-3}/°C, which means there is a reduction of the energy output of 0.45% for every degree Celsius above the 25°C (77°F).

This study is a part of an ongoing research that has been carried on for two years through the conduction of a field experiment and computer simulations. This part of the research examines experimentally the thermal performance of PV modules over two roofing types, which are: green roof (PV-green) and black roof (PV-black). The aim is to compare the roof surface temperatures, air temperatures under PV modules, and underside surface temperatures for PV modules simultaneously across the two roofing types. A black roof membrane was installed under nine PV modules and a green roof was installed under another nine PV modules. A weather station was installed over the CRD roof to record data on ambient temperature, relative humidity, wind speed and direction, and solar radiation. Thermocouples were installed to measure surface and air temperatures across the two roofing types with a five minute interval. A general schematic of the sensor locations is illustrated in Figure 3. Air temperature sensors were placed in between each PV panel and roof surface. Roof surface and PV underside surface temperature sensors were installed at the center of each PV panels. The locations of the sensors are consistent across all the PV panels.

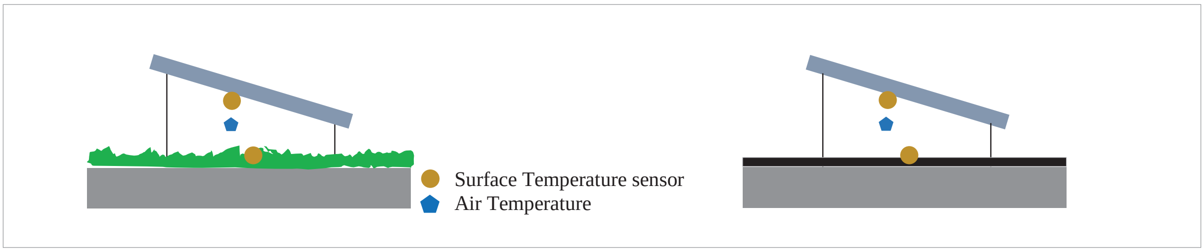

Figure 3: Schematic of sensor type and locations

The data was collected for a one month period (September 2015). As mentioned, PV output decreases over summer months due to the increase in ambient and PV module temperature. Therefore, in order to demonstrate that roofing choice can impact the PV modules operation temperature, sunny days with high ambient temperature were selected. Calibration tests were performed to verify that the experimental bed had similar thermal performance before applying any treatment. During the calibration period, air temperature and underside PV panel's surface temperature were measured for each PV panel.

4. Results

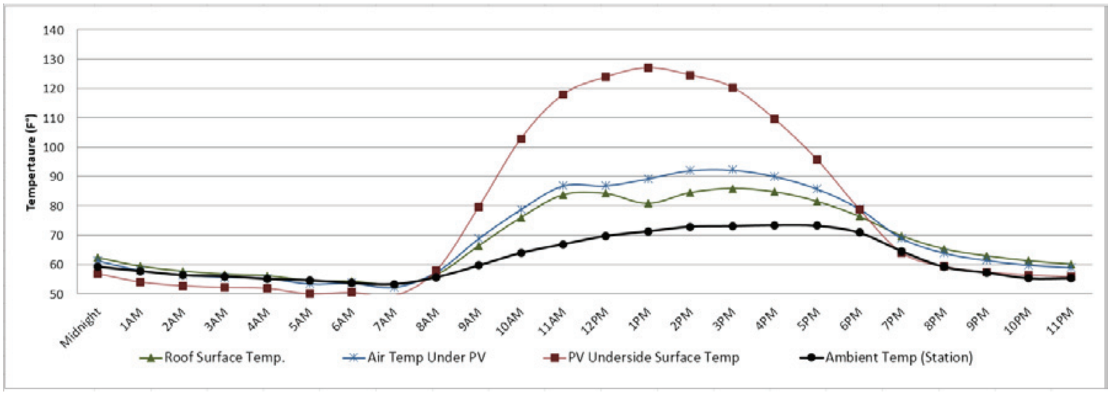

Figure 4: PV-green thermal performance

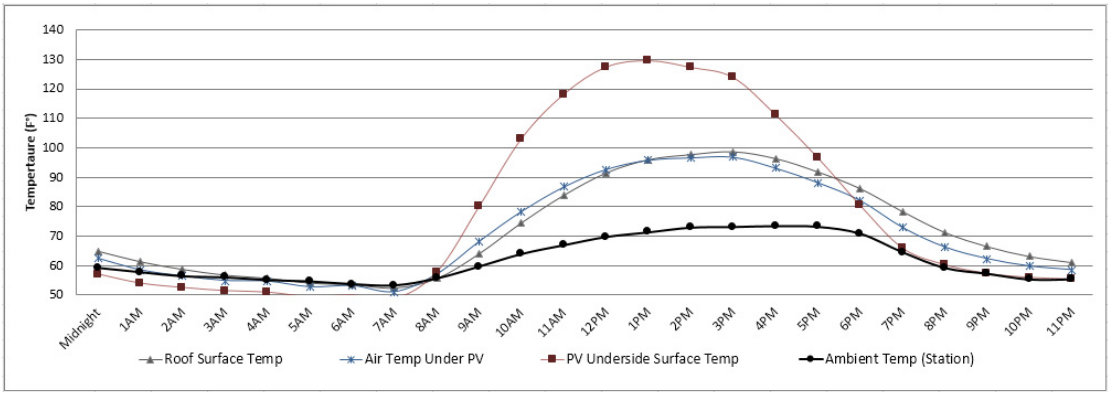

Figure 5: PV-black thermal performance

The thermal performance results of PV-black and PV-green are for data collected between September 25, 2015 and September 30, 2015. PV-green recorded lower temperatures than PV-black throughout the selected dates. Figure 4 and 5 show the results of September 26, 2015 for PV-green and PV-black respectively. The ambient temperatures from the weather station at 1:00 PM was 21.85°C (71.33°F) while the air temperatures under PV-green and PV-black were 31.8°C (89.3°F) and 35.4°C (95.8°F) respectively. PV-green reports 3.6°C (6.5°F) lower in ambient temperature than PV-black. Roof surface temperatures under PV panels show the same profile as the roof surface temperatures under PV panels. Roof surface temperatures under PV-green and PV-black were 27.1°C (80.78°F) and 35.5°C (95.92°F) respectively. The reduction on ambient and roof temperatures also impact PVs underside surface temperature. PV underside surface temperature for PV-green and PV-black were 52.8°C (126.99°F) and 54.18°C (129.52°F) respectively.

PV module that is used for this research is rated with 235W, a conversation efficiency of 14.4%, and a temperature coefficient of $-4.5*10^{-3}$/°C. The PV-green underside temperature on the selected date was 1.38°C (2.53°F) lower than PV-black. PV-green records 29.18°C (52.5°F) over the STC temperature while PV-green records 27.8°C (50°F) over the STC. In term of energy output, PV-black generate 0.62% less energy than PV-green.

5. Future Work

The research is extended to investigate three roofing types simultaneously through a one year field experiment. High reflective roof had been installed in addition to the roofing types presented earlier at this research (green roof and black roof). High reflective roof has been implemented as alternative simulation that reduce the heat transfer via building roofs. The surface temperature of cool roof is lower than the surface temperature of conventional roofing materials [22, 23]. Even in hot summer weather, cool roof surface temperatures generally stay below 50ºC (120°F) [24]. The roofing materials have significant impact to the roof surface temperatures and the air above them.

There is a gap in the literature of the impact of high reflective roof to the PV panel performance. There is no specific result investigate the thermal performance as well as the energy output of PV panel over high reflective roof. In addition, an advance monitoring system had been installed to measure the energy output from PV-green, PV-black, and PV-white. The CDR’s PV array was loaded by central inverter; therefore, new micro inverters from Enphase Energy have been installed. The new system allows to monitor the energy generated on the panel level.

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