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Variations in photovoltaic performance due to climate and low-slope roof choice

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ABSTRACT

With urban space at a premium, roofs are being targeted as an opportunity to deploy sustainable energy technologies for buildings. This research evaluates the combination of green roofs and solar photovoltaics specifically through their temperature and electricity production relationship. Measurements over a one year study period from July 1, 2011 to June 30, 2012 from a large field project in Pittsburgh, Pennsylvania 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 photovoltaic (PV) output. These estimation functions were applied to three different cities (San Diego, CA; Huntsville, AL; and Phoenix, AZ) chosen to represent a wide range of irradiance and temperature values. Based on the specific test-bed configuration, the green or black roof choice under the PV panels had little impact on the PV performance. The difference in magnitude of power generation for green roof–PV compared with black roof–PV assemblies was small (0.5%) corresponding to an annual loss of $9/60 panels in Pittsburgh and a benefit of approximately $8/60 panels per year in Phoenix. Results also suggest that sites consistently above 25 °C (77 °F) will most likely see a small, positive impact from a green roof–PV combination. Building managers and designers should consider this temperature and power output interaction a minor economic factor in roof decisions.

1. Introduction

Building managers are increasingly examining roof technologies to improve the energy performance of buildings. Huang and Franconi [1] found that thirteen percent of heat lost or gained in a building can be attributed to roofs. With national U.S. commercial roof estimates of 2.6–5.0 billion m^2 (28–53 billion ft^2) [2,3], total energy transferred through roofs could be significant.

While conventional roofs occupy the majority of roof space, green (or vegetated) roofs are also being installed, in part, because they can reduce building energy consumption [4]. The three most prominent conventional roofing types (Built-up Roofs, Modified Bitumen, and Single-ply) comprise almost 90% of the national low-slope roofing sales in 2004 [5]. These roofs are the least expensive to install. In contrast, green roofs have less than 1% market share by area [2,6]. Green roofs incorporate vegetation typically over traditional black or white roof membranes. Resulting from the plants and soil medium properties, one potential advantage of green roofs over black roofs is lower energy consumption by mitigating heating and cooling loads to internal building spaces [4,7]. The thermal mass of a green roof decreases diurnal temperature swings at the site into a smaller temperature range [8,9]. By moderating diurnal temperature swings, the heating, ventilating and air-conditioning system works less to keep the internal building spaces at a comfortable temperature. In addition to mitigating internal temperature, green roofs also cool the surface temperature directly above the green roof. Many field experiments have documented lower green roof surface temperatures by 10–40 °C at peak, summer, daytime temperatures through evapotranspirative cooling and improved reflectivity compared to black conventional roofing [10–14]. Also, prior research has developed mathematical models to predict the thermal behavior of green roof components [15–17] and the entire green roof assembly [16–19]. Often these green roof models are validated by field experiments [15,16,18–20] and some are compatible with larger energy simulation programs [16,18,19].

In urban areas, solar technologies have become more common on roofs. Areas that are large in size, contiguous, and without shade are ideal for solar [21,22]. Therefore, roofs are prime space for solar technologies since roofs typically are unused except for heating, ventilation and air conditioning equipment [3,23]. Furthermore,

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Fig. 1. Two designated study areas (black roof–PV and green roof–PV) on the Sunscape Demonstration Project [35] (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.).

electricity produced on the roof for consumption in the building avoids average losses of 7% from transmission and distribution lines when generated at a power plant [24].

Two primary types of photovoltaics (PV) modules are crystalline silicon and thin film. Crystalline silicon (comprising Mono, Poly, and Ribbon) has the longest track record in the solar market and occupies roughly 70–90% of the PV market share [25,26]. Crystalline silicon also has some of the highest PV conversion efficiencies at 15–20% [26–28]. The downsides to crystal silicon technology are its high production cost and weight. Thin Film technology captures the remaining PV market share. While thin film solar is produced more quickly and cheaply than crystalline silicon, efficiency is lower at 6–13% [28,29]. Conversion of sunlight to electricity across technologies can be decreased by dust, hot air temperatures, and shade among other factors [30–32].

Often green roofs and PV panels are installed separately on roofs, but they can exist together harnessing potential co-benefits. Specifically with hot air temperatures, PV panels placed over green roofs (referred to as green roof–PV for this research) can utilize the cooler air to maintain or possibly increase efficiency compared to panels placed over black roofs (referred to as black roof–PV) [9]. Hui and Chan [33] conducted a one day field experiment comparing one PV panel over a black and green roof in Hong Kong on a sunny day. The green roof's surface temperature was 5–11 °C cooler than the black roof's, and the green roof–PV system produced 4% more power. Köhler et al. [34] also carried out a field experiment in Germany by comparing the average PV performance of two green roof–PV assemblies to the average of five black roof–PV systems. During the year 2000, the monthly average of the black roof–PV systems out performed green roof–PV assemblies by −15% to 3%. This wide range comes from differences in panel manufacturers and panel tilt of black roof–PV assemblies.

This study improves on previous literature by quantifying the relationship between ambient temperature and PV output by comparing the performance of green roof–PV and black roof–PV systems over a one year field experiment with the same PV panel type and tilt. The test bed used in this research had a higher number of panels (60) and installed power which is helpful in understanding scaling impacts. In addition, this project has four times more installed power than Köhler's study.

The main dataset for this research was based on one commercial low-slope roof that has adjacent black and vegetated roof sections underneath the same type of polycrystalline PV panels. In 2010, Scalo Solar Solutions, located in Pittsburgh, Pennsylvania, received a Pennsylvania Energy Development Authority grant to transform their 3160 m^2 (34,000 ft^2) roof into a laboratory for testing various types of roof technologies. The roof project was called "Sunscape" and showcases three types of photovoltaic technologies, two types of green roofs, a thermoplastic (TPO) white roof and an ethylene propylene diene monomer (EPDM) black roof, as depicted in Fig. 1 [35]. The roof assembly below the membrane has an *R*-value of 2.96 K m^2/W (16.8 h ft^2 °F/Btu). Sunscape's roof is separated into approximately:

- 1580 m^2 (17,000 ft^2) of white membrane,
- 1226 m^2 (13,200 ft^2) of black membrane,
- 231 m^2 (2490 ft^2) of moss mat green roof, and
- 123 m^2 (1320 ft^2) of sedum green roof.

For this study, only the vegetative moss and black roof surfaces which have the same polycrystalline ET Solar 275 W PV modules tiled at 15° were analyzed. The ET Solar 275 W panel dimensions were 1.96 m by .99 m (77 in. × 39.1 in.), mounted with landscape orientation and faced south. Two other non-polycrystalline PV types and the white roof were used at Sunscape roof but were not included in this analysis. The extensive moss green roof has 60 PV panels (16.5 kW capacity) overtop while the black roof has 90 panels (24.7 kW capacity). A profile schematic of all four Sunscape roof assemblies is illustrated in Fig. 2.

For this research, new regression equations were derived from the Pittsburgh Sunscape data and applied in other climates. Regression functions are a common way to predict photovoltaic cell temperature [36] and power output [37]. Often these functions take a linear form but use varying climate parameters as dependent variables [36,38,39]. These Pittsburgh based regressions were used to estimate the expected difference in PV power from green and black roofs if a combination system were hypothetically located within another climate. Three case study locations (Huntsville, AL; San Diego, CA; Phoenix, AZ) were chosen to represent different climate profiles under a base-case and high temperature scenario. The objectives of both these scenarios were to determine (1) under what climate parameters does cooler air above the green roof increase PV output compared to black roofs, (2) the magnitude of the difference in PV output, and (3) a range of potential outcomes. Results were used to inform interested parties if the green roof and PV temperature relationship is a significant parameter when considering roof design decisions.

The relationship between PV power output and temperature is given by a temperature coefficient. Generally, temperature coefficients are negative and change with different solar irradiance measurements and types of panel [40]. The panel manufacturers provide the temperature coefficient typically in the form $\pm\%P_{max}$/°C [30,41] where P_{max} is the maximum rated power under standard test conditions (1000 W/m^2, 1.5 air mass and a cell temperature of 25 °C). For example, the PV panels used in this research on Sunscape have a −0.46%/°C temperature coefficient which is representative for mono and polycrystalline panels [42,43]. Therefore, operating under 1000 W/m^2 these panels are expected to decrease in maximum power by −0.46% for every 1 °C increase in PV cell temperature above 25 °C [41]. Thin film panels typically have a slightly lower temperature coefficient around −0.25%/°C [42,43,44]. Often PV cell temperatures are recorded between 40–70 °C under clear-sky conditions [45] so the decline in performance could be significant. However, the usefulness of temperature coefficients is limited in the field because climate conditions vary significantly from the standard test conditions [46].

2. Data

Across roof surfaces and PV technologies at Sunscape, data collection included temperature sensors, moisture sensors, air sensors and electricity production meters. For the various roof types, air and surface temperatures were collected throughout the roof assemblies where applicable. PV power is collected on the sub-array level (i.e. collection of 30 panels) after the inverter. The power output