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Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in Combined Systems

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by

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Abstract

Recent studies suggest that integration of photovoltaic panels with green roofs may improve the performance of both. While vegetation may provide a benefit by reducing the net radiation load on the underside of the photovoltaic (PV) panels, it may also affect convective cooling of panels, and consequently, panel efficiency. Both effects likely diminish with the height of the PV panel above the roof, although placing PV panels too close to the vegetation increases the risk of the plants growing over the edges of, and shading the PV panel. There is a gap in the literature with respect to evaluating these competing effects. The present study aims to fill this gap.

Experiments were conducted over a two-month period during summer using two identical PV panels within an array of rooftop-mounted panels. These experiments were performed at two heights (18 cm and 24 cm) using three roofing types: white, black and green (vegetated). Results showed that the mean power output of the system in which the PV panel was mounted above a green roof was 1.2% and 0.8% higher than that of the PV-black roof and the PV-white roof at the 18 cm height. At the 24 cm height, the benefit of the green roof was slightly diminished with power output for the PV panel above a green roof being 1.0% and 0.7% higher than the black and white roof experiments, respectively. These power output results were consistent with measured variations in mean panel surface temperatures; the green roof systems were generally cooler by 1.5˚C to 3˚C. The panel surface mean heat transfer coefficients for the PV-green roof were generally 10 to 23% higher than for the white and black roof configurations, suggesting a mixing benefit associated with the roughness of the plant canopy. As expected, the results

indicate that the best PV panel performance is obtained by locating the PV panel above a green roof. However, the relative benefits of the roof energy balance diminish with distance between the PV panel and the roof.

Moreover, the results of this study showed that the mean power output of the PV panel above the white roof was 0.7% and 0.44% higher than that of the PV panel above the black roof at 18 cm and 24 cm heights, respectively. The results of the power output differences in all the experiments were statistically significant at the 95% confidence interval ($P < 0.01$).

Dedication

I dedicate my accomplishment of this thesis to my lovely country, Iraq, and to its fabulous people who have been facing and suffering from horrible hardships throughout past years. I hope that this achievement will contribute to improving the energy performance of my country.

I dedicate my thesis work to my dear father, who has motivated me immeasurably, and to my beloved mother, who has given me the true meanings of tenderness and love. Additionally, I would like to thank all of my kind family members, who always encouraged me to work hard, and made me optimistic to overcome some very hard and difficult moments.

Finally, my dear wife and daughters, Malak and Mina, you deserve this work. You have given me the energy and inspiration to achieve this research. My task would not have been possible without the help and support of my caring loving wife.

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Table of Contents

Abstract i
Dedication iii
Acknowledgments iv
List of Tables vii
List of Figures viii
Chapter 1: Introduction and literature review 1
1.1. Motivation 1
1.2. Typical Roof Types 3
1.2.1. Conventional black roofs 5
1.2.2. White roofs 6
1.2.3. Green Roofs 8
1.3. Photovoltaic (PV) panels 11
1.3.1. History of Photovoltaics Panels 11
1.3.2. Semiconductor 13
1.3.3. P-n junction and Photovoltaic effect 14
1.3.4. Performance of the PV panels 16
1.3.5. Rooftop Photovoltaic System 18
1.4. Green roofs Integrated with PV Panels 20
1.4.1. Theoretical studies 21
1.4.2. Experimental studies 22
1.5. The Purpose of This Study 27
Chapter 2: Methodology 28
2.1. Test Facility 28
2.2. Experiment layout 29
2.3. Instrumentation 32
2.4. Experiment Design 33
Chapter 3: Results 35
3.1. Analysis method 35
3.2. Control Test Results 36
3.3. Comparison of Roof Treatments at 18 cm Height 38
3.3.1. Green vs. Black Roof at 18 cm 38
3.3.2. Green vs. White Roof at 18 cm 41

3.3.3. Black vs. White Roof at 18 cm 44
3.4. Comparison of Roof Treatments at 24 cm Height 46
3.4.1. Green vs. Black roof at 24 cm 47
3.4.2. Green vs. White Roof at 24 cm 49
3.4.3. White vs. Black Roofs at 24 cm 51
3.5. Evaluating the Role of PV Panel Height 53
3.5.1. Green Roof at 18 and 24 cm 56
3.5.2. Black Roof at 18 and 24 cm 59
3.6. Comparing this study with prior studies 63
Chapter 4: Discussion of Experimental Results 66
Chapter 5: Conclusion 69
References 73

List of Tables

Table 1. Summary statistics for the control test at 18 cm height. 37
Table 2. The results of the PV-green roof in comparison to the PV panel above the white and the black roofs at 18 cm height. 43
Table 3. Results of the PV-green roof vs. the PV-white roof and the PV-green roof vs. the PV-black roof at 24 cm height. 49
Table 4. Weather characteristics measured at the reference rooftop weather station for the comparison periods for green and black roofs at two different heights. 54
Table 5. Linear regressions between convective heat transfer coefficients and the local wind speeds at 18 cm and 24 cm heights for the PV-green roof. 57
Table 6. Linear regressions between convective heat transfer coefficients and the local wind speeds at 18 cm and 24 cm heights for the PV-black roof. 60

List of Figures

Figure 1.1: Roofs as percentage of the total land area of four cities in the USA [9]. 4

Figure 1.2: Types of conventional roofs used in the US in 2004 for re-roofing. Where BUR= built-up roofing; SPF= spray polyurethane foam, after [9]. 6

Figure 1.3: The construction of green roofs [19]. 9

Figure 1.4: The band gaps for insulator, conductor and semiconductor materials, after [31]. 14

Figure 1.5: I-V curve shows how the voltage decreases with increasing the temperature [35]. 16

Figure 1.6: Green roof integrated PV panels in Germany [47]. 19

Figure 1.7: Evapotranspiration, transpiration and evaporation [Source: Wikipedia]. 20

Figure 1.8: Cross section view of the experimental layout of the Köhler’s Study [53]. .. 23

Figure 1.9: The experimental layout of Perez’s study shows the difference in the distance between the panel and the roof; (a) the PV-green roof, (b) the PV-gravel roof [56]. 25

Figure 1.10: The experiment layout of the Chemisana and Lamnatou’s study, (a) PV-sedum, (b) PV-gazania, and (c) PV-gravel [57]. 26

Figure 2.1: The Portland State University GRIPV test facility on the roof of STRC Building. 29

Figure 2.2: The experiments layout: (a) Green and Black surfaces, (b) Green and White surfaces, (c) White and Black surfaces. 31

Figure 2.3: Cross sectional view of the PV panel above the green roof showing the positions of the sensors. 33

Figure 2.4: Control test on panel A and C. 34

Figure 3.1: Hourly mean surface temperature for the panel A (T_A) and the panel C (T_C) at the control test. 37

Figure 3.2: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the green-black roof experiment at a height spacing of 18 cm. 39

Figure 3.3: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the green-white roof experiment at a height spacing of 18 cm. 42
Figure 3.4: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the white-black roof experiment at a height spacing of 18 cm. 45
Figure 3.5: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the green-black roof experiment at a height spacing of 24 cm. 47
Figure 3.6: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the green-white roof experiment at a height spacing of 24 cm. 50
Figure 3.7: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the white-black roof experiment at a height spacing of 24 cm. 52
Figure 3.8: Wind rose shows the wind speed and its direction (a) Aug.2, (b) Aug.25, for the period from 10 am to 3 pm. 55
Figure 3.9: Results for the (a) convection coefficients, (b) temperatures, and (c) power output of the PV panel above the green roof at 18 cm and 24 cm heights.... 57
Figure 3.10: Comparison of convective coefficients between the 18 cm and 24 cm heights of the PV-green roof. 59
Figure 3.11: Results for the (a) convection coefficients, (b) temperatures, and (c) power output of the PV panel above the black roof at 18 cm and 24 cm heights. ... 61
Figure 3.12: Comparison of convective coefficients between the 18 cm and 24 cm heights of the PV-green roof. 62

Chapter 1: Introduction and literature review

1.1. Motivation

On hot sunny days, photovoltaic panels become hot. The photovoltaic cells and other semiconductors are sensitive to temperature. When the temperature of the solar cells increases, the open circuit voltage decreases, thereby reducing the power output of the solar cell [1]. The sensitivity of PV panel power output to operating temperature is typically on the order of 0.15- 0.4% per ˚C for thin film silicon and 0.35-0.5% per ˚C for crystalline silicon cells, respectively [2]. In other words, when PV panel temperatures go above 25˚C, which is the standard test temperature, the efficiency of PV panels will drop to the percentages above based on the PV panel type. Thus, the prospect of finding passive or active means of cooling PV panels offers promise for improving panel performance. This opportunity is particularly relevant as the climate warms and as PV panel systems are increasingly deployed in warmer urban settings.

The common method to cool PV panels by using mechanical components like fans or pumps is called active cooling. For example, spraying water on PV panels or flowing a film of water over PV panels reduces the PV panels' temperature. Another example of active cooling is forced air cooling. This method requires a mechanical ventilation system to deliver a continuous stream of airflow over the panel surface. PV panels can be cooled passively, e.g., without mechanical components. One example of passive cooling is the use of a water tank and tubing system in a free convection loop above the solar panels. Cool water is delivered to the lower section of tubing mounted on the underside of the panel. The warm panel heats the water in the tube. Due to differences in the density between the cool and hot water, the water will flow and free convection cooling system is established.

There is a growing tendency to use “cool” roofs to reduce the PV panel temperature. A cool roof is defined a roof that has a high albedo (reflectivity to solar radiation) and high emissivity. Due to these radiative properties, the cool roofs aim to decrease the PV panel temperature by keeping the surfaces of these roofs cooler. It has been observed that temperatures of cool roofs are lower than conventional roofs by as much as 28˚C [3]. However, radiative properties of cool roofs degrade as they age. After one year of operating, the albedo of a cool roof may decrease by up to 20%. Cleaning helps to restore the cool roof reflectivity approximately 90% of its original value [4]. On the other hand, there is also a growing interest in using vegetated green roofs under PV panels to reduce their temperatures and provide multiple benefits to buildings and the environment. Green roofs do not require cleaning but may require other maintenance such as weeding and irrigation.

The use of the rooftop mounted photovoltaic (PV) panels have increased dramatically. Recently, there has been an increased interest in combining PV panels with vegetated green roofs. It has been hypothesized and there is recent evidence to suggest that this combination may improve the performances of both of the green roof and the PV panels. However, there are potentially two competing mechanisms that should be evaluated. While vegetation may provide a benefit by reducing the net radiation load on the underside of the PV panels, it may also affect the magnitude of convective cooling of the PV panel due to inhibiting of airflow (an adverse effect), or increased turbulent mixing (a beneficial effect). Both of these effects would depend upon the spacing between the PV panels and the roof surface. There is a gap in the literature with respect to comparing these competing heat transfer mechanisms. The present study aims to bridge this gap by investigating the surface convection coefficients for panels at various heights above conventional and green roof surfaces.

1.2. Typical Roof Types

In new constructions applications, rooftops are being considered as a means to improve energy efficiency in buildings. Most buildings' conservation and efficiency designs have considered the buildings interiors, neglecting essential advantages from roofs. In a modeling study of the US commercial building stock, it was found that an average of 13% of the energy gained or lost was through roofs [5]. Historically, rooftops have been used mainly for protection from outdoor conditions. However, new technologies have tried to complement these traditional perspectives. Multiple roofing technologies have been developed for generating electricity, reducing stormwater runoff, mitigating the urban heat island (UHI) effects, or reducing energy consumption.

Roofs represent an important fraction in the construction applications. Roofs are an important element of the built environment, accounting for approximately 20 -25% of the total surface area in cities. For example, roofs cover 20% of the total land area in four cities (Chicago, Houston, Sacramento, and Salt Lake City) in the United States as shown in Figure 1.1 [6, 7].

There are two types of roofs. Firstly, roofs that have a slope of more than 1:12 are called steep-slope roofs. Most roofs of residential buildings are steep-slope roofs. Secondly, low-slope roofs are roughly flat and they have a slope of less than 1:12 to let water drain away. Most roofs of commercial buildings are categorized as low-slope roofs. The majority of the low-slope roofs are conventional roofs. The most common types of conventional roofs are modified bitumen, built-up roofs, and single-ply which are the least expensive to install and normally darker in color. Vegetated green roofs and white roofs are now competing against conventional roofs, but so far have succeeded in gaining market share of 1% and less than 10%, respectively [8,9]. In the following subsections, the conventional roofs, white roofs and vegetated green roofs are described to better understand the roofing types that were used in this study.

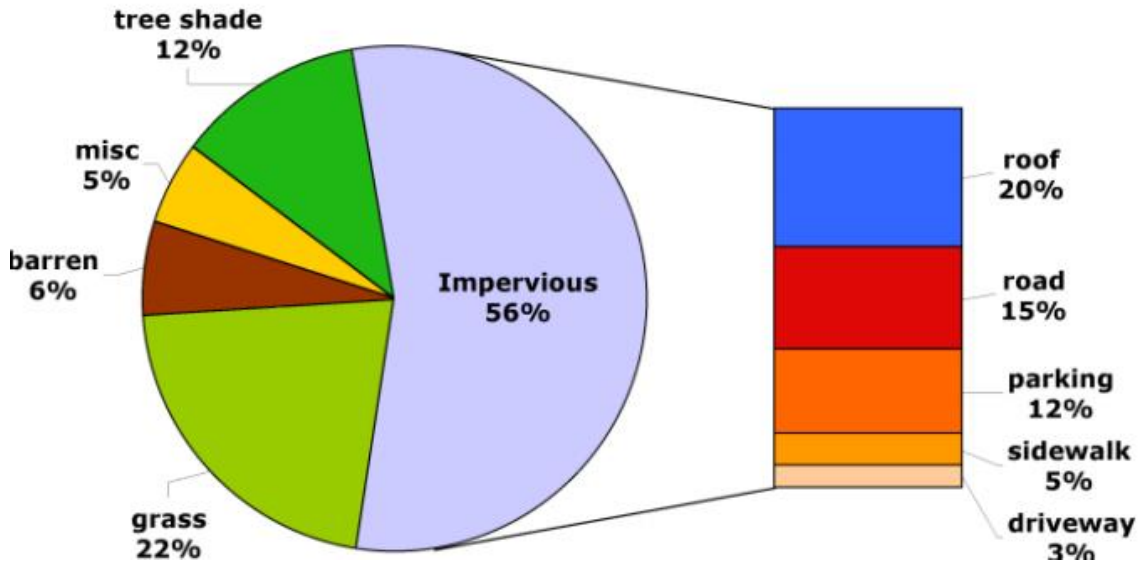


Figure 1.1: Roofs as percentage of the total land area of four cities in the USA [9].

1.2.1. Conventional black roofs

The most common conventional roofs are single ply, built-up roofs and modified bitumen, representing 46%, 18% and 20%, respectively, of the re-roofing of buildings in the United States in 2004, as shown in Figure 1.2 [9,10]. Ethylene Propylene Diene Monomer (EPDM) membranes occupy 27% of the market share within the single-ply. The lifespan of these roofs is between 10 to 25 years. For example, the lifespan of a single-ply EPDM is approximately 15 years, while the lifespan of modified bitumen is between 20-25 years. The installation costs of these roofs are less than that of vegetated green roofs. The surface temperatures of the conventional black roofs reach 90˚C in afternoon hours during summertime [9]. Due to the high absorptivity of conventional roofs, these roofs absorb more solar radiation than the green and white roofs. The conventional black roofs are more beneficial in cold climates because they absorb 90% of the sun’s energy. However, the conventional roofs are not suitable in warm climates for multiple reasons. These roofs increase indoor temperature because they increase the heat flux into buildings. Consequently, they increase energy used by air conditioners. In addition, these roofs have negative effects on cities. These roofs increase the peak energy demand during afternoon hours due to hot indoor temperatures. They increase greenhouse gas emissions from the power plant and increase the urban heat island effects [8].

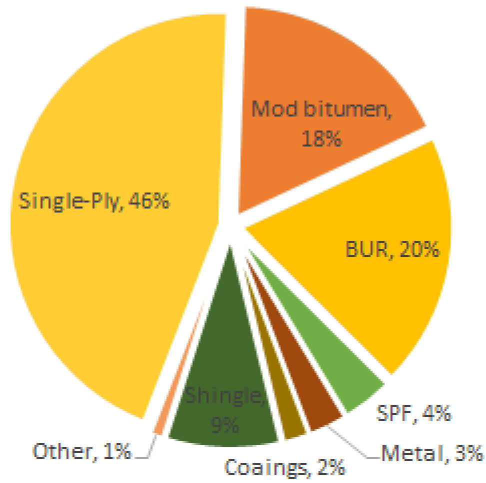


Figure 1.2: Types of conventional roofs used in the US in 2004 for re-roofing. Where BUR= built-up roofing; SPF= spray polyurethane foam, after [9].

1.2.2. White roofs

White roofs are referred to as cool roofs. Even in extremely hot weather, the surface temperatures of the white roofs stay below 50˚C while surface temperatures of darker roofs reach 90˚C or higher [9]. There are two types of white roofs: white coatings and single ply membranes. The single-ply membranes have four types: Polyvinyl Chloride (PVC), Thermoplastic Polyolefin (TPO), Ethylene Propylene Diene Monomer (EPDM), and Chlorosulfonated Polyethylene (CSPE). Due to the high albedo (capability of the surface to reflect the solar radiation) of white roofs, they reflect more incoming solar radiation than black roofs. As a result, the white roofs cause the surface temperature to be cooler which could reduce heat transfer into the urban environment as well as into the buildings. Several studies in different climates showed that the white roofs decreased the roof surface temperatures 20-42˚C compared to black roofs [11-13]. However, after initial installation of the white roof, the accumulation of dust and dirt can influence the albedo of the roof. As we mentioned previously, It has been shown that the albedo of the white roofs declined by an average of 0.15 during the first year after the installation of roofs. However, the albedo can recover about 90% of its original value if the roof is cleaned [1].

The benefits of white roofs are divided into both private and public. Private benefits can accrue to building owners and occupants. White roofs decrease heat flux into buildings in summer, leading to reducing of cooling costs and keeping the building cooler and more comfortable. It has been shown that the indoor temperature can be more than 3˚C cooler when a cool roof is added; thereby allowing for a reduction in size of air conditioning equipment [9]. White roofs are more beneficial by saving energy in warm climates with high solar radiation [14]. It was found that white roofs reduce summertime air conditioning energy by 10-50% compared with black roofs [8, 15, 16].

Public benefits are enjoyed by the community as a whole. On a city scale, white roofs mitigate the urban heat island effect and reduce the peak energy demand. Recent research has demonstrated that peak electricity demand increased by 2-4% for each 1˚C increase when daily temperatures go above the threshold of 15 to 20˚C [17]. In addition, white roofs reduce the greenhouse gas emissions from generators by reducing the energy demand, thus decreasing ground level ozone concentrations. Ozone, which is a primary part of smog, is formed by the reaction between the volatile organic compound (VOCs) and nitrogen oxides (NOx). Hot ambient temperatures enhance the reaction. Therefore, cooler ambient temperatures decrease smog formation, thus using cool roofs can reduce the smog levels by 10% [9, 18].

1.2.3. Green Roofs

A green roof consists of a soil and vegetation layer as its outermost surface. The construction between the roof structure and the soil (also referred to as growing media) varies from one green roof to another, but usually contains a drainage layer, a root barrier and a protection layer, as shown in Figure 1.3 [19]. Based on the thickness of the growing media, there are two types of green roofs. When the thickness of the growing media is higher than 20 cm, the green roof is referred to as an intensive, or high profile green roof. However, green roofs with growing media thickness of less than 20 cm are more common and are typically referred to as extensive, or low profile green roofs. The temperatures of the vegetated green roof surfaces can be lower than the ambient temperatures, while the temperatures of the conventional roof surfaces can be higher than the ambient temperatures by as much as 50˚C. A study in Chicago investigated the temperatures of vegetated green roof surfaces in comparison to temperatures of conventional black roof surfaces in summertime. It was found that the temperature of the vegetated surfaces was approximately 35˚C cooler than the temperature of the black roof surfaces. In addition, the study showed that the ambient temperature above the green roof was 4˚C cooler than that of the black roof [20].

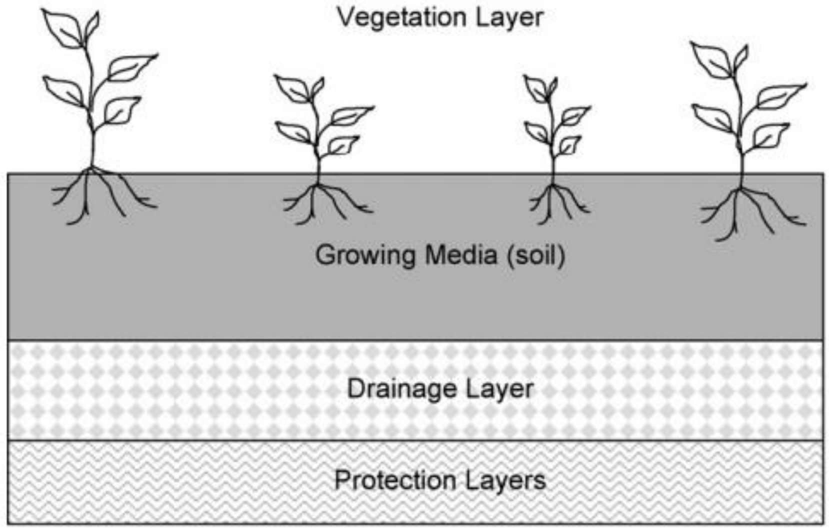


Figure 1.3: The construction of green roofs [19].

Although green roofs have a long history, dating back to ancient times, there lately has been an increased interest in the technology. Many studies have shown that the use of green roofs provides multiple ecosystem services [21-24]. Potential advantages of green roofs involve improved air quality, aesthetic appeal, temperature regulation in the building and surrounding environment, habitat, energy conservation, storm water reduction and building envelope preservation [25]. There have been a number of studies showing the benefits of using green roofs in terms of saving building energy. For example, Ascione et al. [26] used the Energy Plus software to investigate the benefits of green roofs under European climates. The results showed that the green roofs in warm climates could provide up to 11% savings in annual cooling energy, whereas, in cold climates green roofs could provide up to 7% savings in annual heating energy in the building sector. Another field study was performed on the roof of a two-storey building at the University of Central Florida to evaluate summertime effects of green roofs in comparison with conventional roofs on the building sector. The results showed that the average daily maximum temperature for green roofs was 22˚C cooler than that of conventional roofs. Moreover, this study showed that the average heat flux rate through the roof of this building for the green roof was 18.3% less than the average heat flux rate for the conventional roof [27].

Green roofs can also assist in stormwater retention. For example, DeNarado et al. [28] investigated the stormwater mitigation by green roofs. In this study, green roofs were evaluated to find their potential to decrease stormwater runoff. The experiment was performed on small buildings (1.8 m by 2.4 m) consisting of a conventional and green roofs, each with a 1:12 slope. Hydrology data were gathered from three identical buildings. The average porosity of the green roof media was 55 (m^3. m^{-3}) and a field capacity of 34 (m^3. m^{-3}). Based on the data collected in October and November 2002, it was found that the green roofs delayed the runoff an average of 5.7 h. Furthermore, a study of a neighborhood in Merida, Mexico found that green sustainable strategies might also decrease greenhouse gas emissions related to energy consumption. Specifically, the study found the implementation of green spaces and eco-technology could decrease carbon emissions by up 1.06 ton CO2eq/year [29].

1.3. Photovoltaic (PV) panels

Photovoltaic panels convert solar radiation into electrical energy with minimal adverse environmental consequences. Recently, the PV panel technology has been very popular due to several factors such as reductions in PV panel and installation costs, performance increases, and coincident increases in costs of conventional power production. The following subsections describe the PV panels in order to understand the principles of the PV panels.

1.3.1. History of Photovoltaics Panels

The foundation for photovoltaic technology was developed in 1839 by a French physicist, Edmund Bequerel. He discovered that when some materials were exposed to light, they generated a small amount of electricity. In 1883, the first photovoltaic cells were built from selenium. Due to the high cost of selenium in comparison with the amount of the electricity that they generated, the photovoltaic cells using selenium have not become widely used for electricity production [30]. In 1905, Albert Einstein depicted the nature of light and in 1921 the Noble Prize was given to him for his demonstration of photovoltaics. The first viable photovoltaic cells were developed in 1954 from silicon by Bell Laboratories, but their efficiencies were only 4%. These efficiencies were later increased to 11%. In that time, the PV panel technology was not used because the cost of the PV panels was very expensive relative to other alternatives. However, the use of PV panels started to gain traction when a small array of cells was used in 1958 by the United

States Vanguard space satellite to power its radio [31]. The space scientists recognized that the photovoltaic cells could be an efficient source of energy for multiple space missions.

Photovoltaic technology has recently become popular in the United States. The installed photovoltaic capacity increased 54% in the United States between 2009 and 2010. Despite this growth, in 2013 photovoltaic panels provide less than 1% of electricity in the United States [32]. The increased interest in the PV panel technology can be attributed to reducing the costs of PV panels and increasing the PV panel efficiencies. Mainly, there are two types of photovoltaic panels: crystalline silicon and thin film. Crystalline silicon is the most common PV panel in use and occupies approximately 80-90% of the PV panel market share. Because the crystalline silicon is a poor absorber of light, it needs a considerable thickness of material. PV panel efficiencies of the crystalline silicon reach 19% [33]. The construction of the crystalline silicone cell consists of seven layers: cover glass, antireflective coating, contact grid, N-type silicon, P-type Silicon and back contact. The high production cost and weight are considered the downsides to crystalline silicon PV panels. Thus, it is important to find materials that are strong light absorbers. The thin film PV panels have less market share in comparison to crystalline silicone PV panels. Their market share is roughly 10-20%. The construction of the thin-film panel is similar to the crystalline silicon panel construction but the thickness is less. Because the thin film panels are thinner and more flexible, they are commonly used in building integrated photovoltaics. The film PV panels are cheaper than the crystalline silicone PV panels, but with a lower efficiency of 13% [33, 34].

1.3.2. Semiconductor

It is helpful to understand atomic structure in order to understand the principles behind the performance of semiconductors and their usage in the photovoltaic panels. The outermost band of an atom is called the valence band and electrons in this band determine how the atom will act with neighbor atoms. In the valence band, some electrons may be so active and a small amount of force can cause them to jump into a higher band. Thus, they will be free to participate in the conduction. The higher band is called the conduction band. The energy difference between the valence band and the conduction band is called the energy gap or band gap. Materials that have large energy gaps are called insulators. The bonds between atoms in insulators are very strong. Materials in which the valence band is almost empty, and the energy gap is very small, or the valence band and the conduction band are overlapping, are called conductors. Conductors have very weak bonds between neighbor atoms, and these bonds can be easily broken. Materials that have a small energy gap and partly filled valence band are called semiconductors, which are illustrated in Figure 1.4 [31]. Semiconductors have moderately strong bonds between the neighbor atoms. Thus, some of these bonds will be broken and free electrons can jump from the valence band into the conduction band

When impurity atoms are introduced into pure semiconductors, these new crystals are called extrinsic semiconductors, while the pure ones are called intrinsic semiconductors. If the impurity atoms have more electrons in the valence band than the semiconductor atoms, they are called the n-type of semiconductors. On the other hand, if the doping materials have fewer electrons in the valence band than the semiconductor atoms, they are called the p-type of semiconductors.

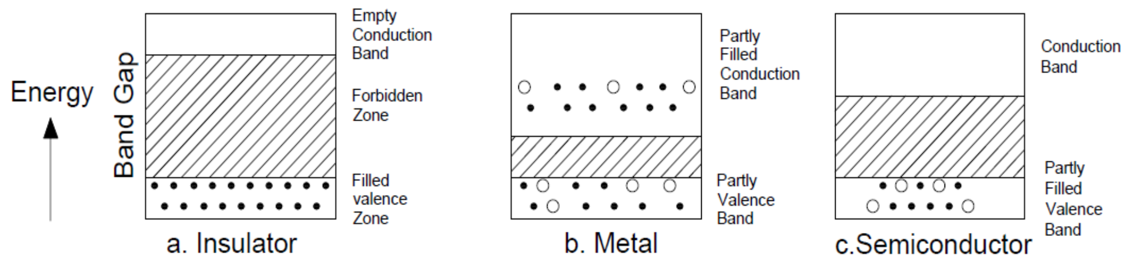


Figure 1.4: The band gaps for insulator, conductor and semiconductor materials, after [31].

1.3.3. P-n junction and Photovoltaic effect

As mentioned earlier, the dopant atoms in n-types have more electrons in the valence bands than the semiconductor atoms. If the excess electrons of the impurity atoms are removed, the dopant atoms will be positively charged (positive ions). In a p-type, the dopant atoms have fewer electrons than the semiconductor atoms, so the dopant atoms have holes and try to adopt excess electrons. Therefore, when the dopant atoms get excess electrons, the dopant atoms will be negatively charged (negative ions). This scenario happens at the junction when an n-type and a p-type are combined. Because there are many mobile electrons in n-types, the free electrons in the n-type diffuse to the p-type in the junction area due to random thermal motions of these electrons. However, there are many holes in a p-type crystal, which diffuse across into the n-types. Thus, close to the junction area, due to the movement of the electrons from the n-type side to the p-type side, the n-type has positive charges while the p-type has negative charges. The idea of the p-n junction is the fundamental principle of the photovoltaic cells' work.

When light impinges a surface, it is either reflected, absorbed, or transmitted. The electrons in the valence band absorb the energy of the photons. If the energy of the photon is higher than or equal to the energy of the energy gap, the electrons can jump into the conduction band. If the energy of the photon is less than that of the energy gap, the electrons will not have enough energy to reach the conduction gap. Thus, this excess energy will lead to an increase in temperatures [31, 35]. If the photon energy is higher than the energy gap, the excess energy increases the kinetic energy of the electrons as well as the temperatures. In addition, increases the temperature lead to decrease the band gap. When the band gap decreases, the open-circuit voltage decreases. Therefore, when the temperature increases, the efficiency of the photovoltaic cells decrease because the voltage decreases with increasing the temperature of the PV panel, as shown in Figure 1.5 [35]. It is important to note that the reason for low efficiencies of the photovoltaic cells is that each photon can free up only one electron.

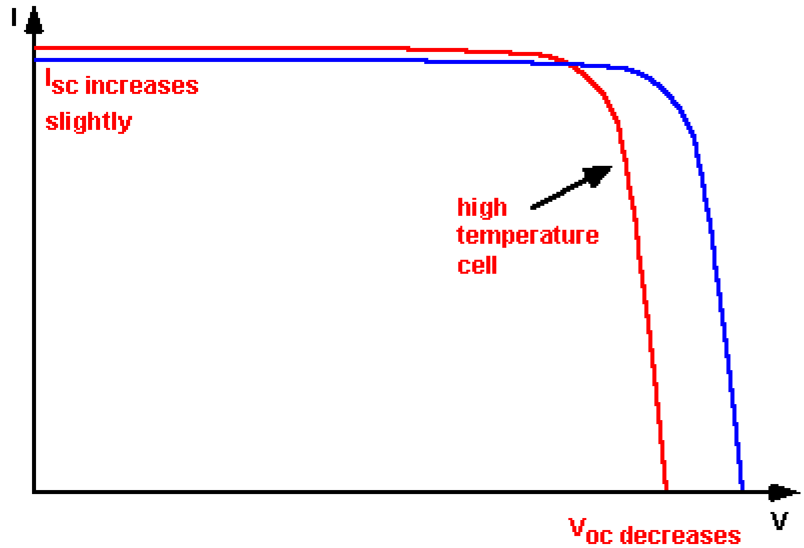


Figure 1.5: I-V curve shows how the voltage decreases with increasing the temperature [35].

1.3.4. Performance of PV panels

The electrical efficiency of PV panels is the ratio of the power output delivered by the panel to the amount of incident solar radiation. The efficiency of PV panels is affected by various factors such as dust, wind, radiation, tracking systems or fixed installation, surface materials, cell temperature, and cells' material. It has been demonstrated that the PV panel performance can increase by 1.5% after cleaning of panel surfaces [36]. When the dust accumulates on the PV panel, this dust could block the sunlight and increase the PV panel temperature. In addition, a study in Iran showed that spraying water over the PV panel on a summer day from 8 am to 5 pm increased the power production by 17% [37]. Spraying water over PV panels helps to clean the PV panels from the dust and reduce the temperature of the PV panels. Another study showed that the instantaneous peak power output of the PV panel increased by 26% using continuous pumping water [38].

The tilt angle and the orientation of the PV panels influence power productions of PV panels. In summer, the tilt angle should be equal to 15˚ minus the latitude of the location of the PV panel to capture more sun light because the sun in summer is high in the sky. In winter, the tilt angle should be equal to 15˚ plus the latitude because the sun in winter is low in the sky. However, to capture more sunlight during the whole year, the tilt angle should be equal to the latitude. In addition, the orientation of the PV panel is considered an important factor that affects on the yield of the PV panel. True south and true north are ideal orientations of the PV panels in the northern hemisphere and the southern hemisphere, respectively. Another factor that influences the PV panel temperature is the wind speed. Research showed that the PV panel temperature decreased 1.4˚C per m/s wind speed increase [39]. The PV panel efficiency decreases when the PV panel temperature increases and the cells show long-term degradation if the cell temperature goes above a certain limit [40]. The electrical efficiency (η) of PVs reduced by about β= 0.4%/˚C for crystalline silicon solar cells [41]:

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

This illustrates the potential to improve PV panel performance through provision of an environment that maintains the PV panels at a lower temperature.

1.3.5. Rooftop Photovoltaic System

Rooftop-mounted photovoltaic (PV) panels are becoming increasingly common. Areas that are big and without shade are perfect for solar panels. Therefore, rooftops are good spaces for PV panels since the rooftops usually are unused except for air conditioning, ventilation and heating equipment [42, 43]. The integration of PV panels (BIPV) on buildings began in late 1970s. The first building in the United States with BIPV was built in 1980. Nowadays, the BIPV system is very popular. Suitable area of rooftops to install PV panels was about 5.7 billion square meters in 2003, while it was estimated to be approximately 7.8 billion square meters in 2013 in the United States [44]. The installed PV capacity in the United States has increased dramatically in recent years. During 2007 and 2008, the installation capacity increased by 63% in the United States due to federal and state support. The installed PV panel capacity on rooftops accounted for 64% of the total installation while the building integrated PV panel accounted for 10% [45].

As mentioned previously, the surface temperatures of the conventional roofs reach 90˚C while using vegetated green roofs can reduce the surface temperatures. Nowadays, some people prefer using green roofs for improving building thermal performance and energy saving. Others are interested in using PV panels on rooftops for electricity production. There is a competition between roof-mounted PV panels and green roofs for limited rooftops space [46]. However, when green roofs integrate with PV panels, this integration can improve their effectiveness and functions by shading and cooling effects. The cooling effect from the soil and plants may reduce the temperature of

PV panels. Additionally, shading of the green roof by PV panels may reduce irrigation needs while simultaneously improving plant health and biodiversity of the green roof system. Green roofs integrated PV panels were first used in Germany in 1999, as shown in Figure 1.6. Several green roofs integrated photovoltaics have been installed worldwide, such as in the United States (Portland State University) and in Switzerland (Basel and Zürich).

Figure 1.6: Green roof integrated PV panels in Germany [47].

When we talk about the combination of green roofs with PV panels, it is necessary to define the evapotranspiration. Evapotranspiration is the combination of the evaporation and the transpiration as shown in Figure 1.7. Evaporation is the process of changing the phase of water from a liquid to a gas. This water comes from the soil and the vegetated surfaces. Transpiration is the movement of water through the plants from their roots to their leaves emitted as a vapor through stomata. Many factors influence the rate of evapotranspiration. The rate of evapotranspiration increasing is proportional to temperature. Transpiration increases because at high temperatures the stomata of plants' leaves open up to release water. The evaporation increases because the amount of the energy to transform the water from a liquid to a vapor is high. Another influence on the rate of the evapotranspiration is the wind speed. When the wind speed increases, the rate of evapotranspiration increases. In addition, the plant type, soil type, and soil moisture also affect the rate of evapotranspiration [20, 48].

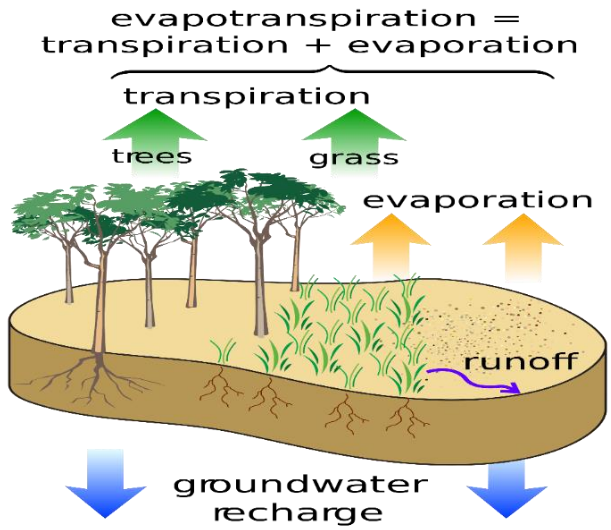


Figure 1.7: Evapotranspiration, transpiration and evaporation [Source: Wikipedia].

1.4. Green roofs Integrated with PV Panels

In addition to the conventionally accepted benefits of green roofs, there is a growing interest in the integration of green roofs with rooftop-mounted photovoltaic panels as a way of improving the performance of both systems. It has been hypothesized that this integration may improve the performance for both the green roofs and the PV panels. Thus, there have been multiple theoretical and experimental studies to evaluate the performance of the PV panels integrated with green roofs.

1.4.1. Theoretical studies

Regarding the combination of the PV panels with vegetated green roofs, there have been several theoretical and modeling studies that have investigated the benefits of this combination. For example, Scherba et al. [49] studied the effect of the roof reflectivity and found that replacing a black membrane roof with a PV-covered green roof or a PV-covered white roof reduced the total sensible flux by approximately 50%. In this research the Energy Plus software was used to investigate the effect of roof reflectivity. Furthermore, the above mentioned study also included an experimental component to validate the EnergyPlus model. Measurements were taken on the roof of the Science Research and Teaching Center (SRTC) Building at Portland State University, Portland, Oregon.

Another important study is that of Hui and Chan [50] in which the results for one year of a building energy simulation (using Energy Plus software) for a low-rise commercial building revealed that PV-green roofs produced 8.3% more electricity than the equivalent PV panel system installed over a conventional roof. It is important to note that the PV panel system in that study was a conventional roof-mounted with a few centimeters gap between the roof surface and the PV panels, whereas the PV system mounted above the green roof had a gap that was larger than the gap of the PV-conventional roof. As a result, there was very little air circulation on the underside of the panels for the conventional installation, and the difference between the PV- conventional roof and the PV-green roof is anticipated to be higher. In addition, the Hui and Chan study also involved an experimental component: measurements were conducted on a rooftop garden in the University of Hong Kong on a sunny day from 11:00 am to 2:00 pm. In this experiment, two identical PV panels were set on a green roof and a bare roof. The results showed that the temperature on the upper surface of the PV panel above the green roof was 5 to 11˚C cooler than the temperate of the PV above the bare roof. The PV-green roof generated 4.3% more electricity than the PV-bare roof. In addition, the results of this study showed that the shading of the PV panel decreased the temperature of the green roof surface by 5˚C in comparison with the green roof without PV panels.

Moreover, Witerman and Brownson [51] and Witerman [52] promoted a model for green roofs, based on microclimate effect and energy balance. In the framework of this research, an energy balance model of a green roof integrated photovoltaic was developed. Transient simulations in different locations in the United States showed a small efficiency improvement (0.08 to 0.55%) in power output.

1.4.2. Experimental studies

With respect to experimental studies of the integration of PV panels with green roofs, Köhler et al. [53] studied different PV-green roof configurations, as illustrated in Figure 1.8, primarily with sedum species in Berlin. A comparison was made between these configurations and PV-Bitumen roofing combinations. The results showed that combining PV panels and green roofs increased the efficiency of the PV panels. In this study, infrared technology was used to measure the temperature of the roof. On July 6, 2004 during afternoon hours, the temperature distribution showed that the green roof surface was about 20˚C cooler than the Bitumen roof. Based on five years' data the effect of the combination of PVs with green roofs was estimated to increase power output by an average of 6%. It is important to mention that this high difference in the power production was not just because of the green roofs. Several factors might contribute to differences such as tracking systems, different inverters, or different tilt angles. In addition, it was found that the combination of the PV panels with green roofs had a positive effect on the environment by reducing the Urban Heat Island effects. The integration of the PV panels with green roofs decreased CO_2 emission by 33 Kg/year. The study authors noted that since there were several interacting effects, it would be beneficial to extend this research to obtain results from other locations for comparisons.

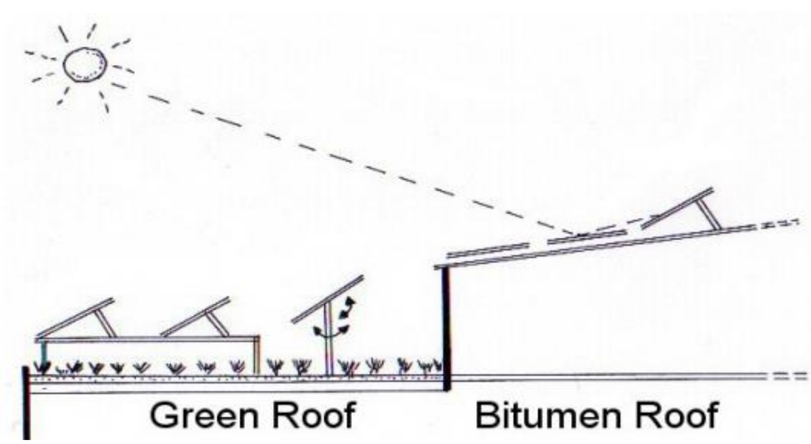


Figure 1.8: Cross section view of the experimental layout of the Köhler's Study [53].

In yet another study, CIGS (Cadmium-Indium- Gallium di –Selenide) PV cylinders integrated with a sedum green roof were investigated at Penn State's 2009 "Natural Fusion" home, which was entered in the 2009 Solar Decathlon. A performance improvement was claimed; however, in this research, the specific results regarding the PV efficiency were not presented [54].

Another experimental study conducted in Pittsburg, Pennsylvania evaluated the combination of PV panels with green roofs through observations of power output and temperature. The measurements were taken over one year from July 1, 2011 to June 30, 2012 from a large field experiment to investigate the difference in power generation from PV-green roofs and PV-black roofs as well as to deduce two regression functions for the PV panel power output and the underside surface PV panel temperature. This study showed that when the ambient temperate became higher than 25˚C and/or the irradiance more than 800 W/m², the PV panels above the green roofs produced more power output than PV panels above the black roofs. The results revealed that the PVs-green roof produced a small positive impact of 0.5% in power output in July, whereas in December the PVs-black roof generated 2% more power output. However, for the entire year, the power output of PVs-black roof was higher than the power output of the PVs-green roof by 0.5%. In addition, it is important to note that the climatic conditions in Pittsburg were approximately 90% of solar irradiance values less than 800 W/m² and 73% of ambient temperature lower than 25˚C [55].

Another experimental study was that of Perez et al. [56]. In this study, there were four small-scale roof systems, including green, gravel, PV-green and PV-gravel on small model houses evaluated over the period May 30, 2011 to January 25, 2012 in New York City. In this investigation, different sedum species were used. The variability of surface temperatures on the PV-green houses were 10.69% less than on the gravel house in June. The average internal and surface temperatures were 5.1% and 1.73% less on the PV-green roof than on the gravel one, respectively. The results revealed that the power output of the PV-green roof was 2.56% higher than the power output of the PV-gravel roof in June 2011. It is worth mentioning that the distance between the PV-green roof and the green roof surface was higher than that of the PV-gravel roof. The authors did not mention the distances, but we can see the difference in distances between the two systems in Figure 1.9. Thus, there would be more airflow passed under the PV-green roof and this decreased the temperature of the PV panels.

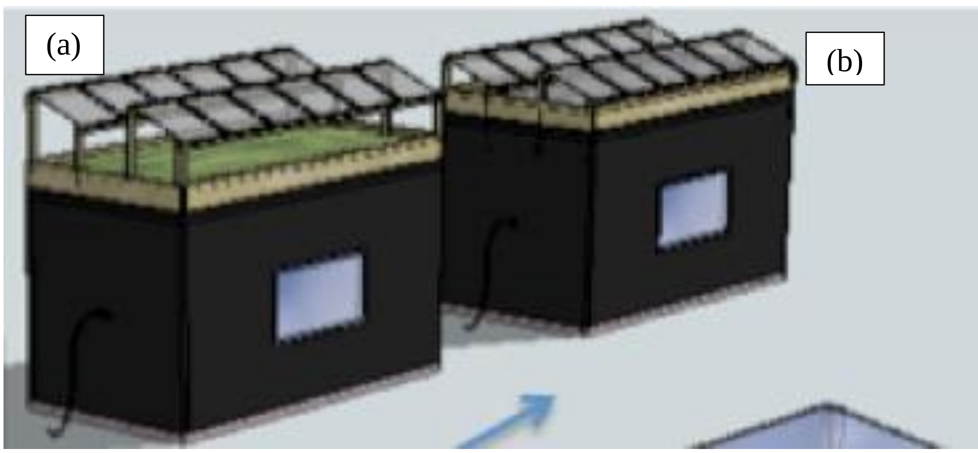


Figure 1.9: The experimental layout of Perez's study shows the difference in the distance between the panel and the roof; (a) the PV-green roof, (b) the PV-gravel roof [56].

Another relevant experimental study was that of Chemisana and Lamnatou [57]. In this study, three small –scale roof configurations, including PV-sedum, PV-gazania and PV-gravel, were performed over two months (June-July 2013) at the University of Lleida, in Spain. Three experiments were performed and each experiment was conducted with pairs of test surfaces as shown in Figure 1.10. The results showed that the mean maximum power generation of five days increased for the PV-sedum and the PV-gasania of 3.33% and 1.29%, respectively, in comparison with the PV-conventional roof. Moreover, the temperature of the PV panel above the gazania green roof was lower than the temperature of the PV panel above the gravel roof (4.2% in average). The differences in the values between the PV panels above green roofs are related to the differences between the two plants: the sedum is a succulent and has thick leaves while the gasnania has narrow leaves and flowers. It has been found that characteristics of sedum leaves enhanced the effective incident irradiance on the panel about 1.43% more than the gazania plant. This study showed that under Mediterranean climatic conditions, PV panels above green roofs were more beneficial than PV panels above gravel roofs.

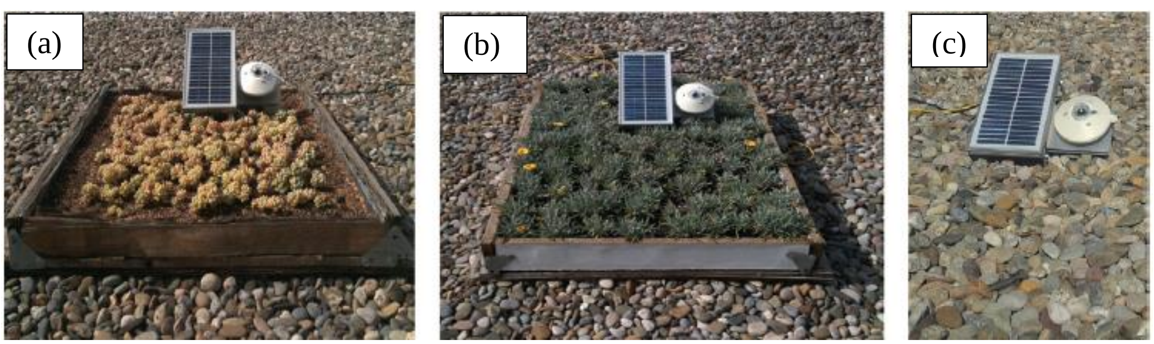


Figure 1.10: The experiment layout of the Chemisana and Lamnatou's study, (a) PV-sedum, (b) PV-gazania, and (c) PV-gravel [57].

1.5. The Purpose of This Study

Based on the evidence gathered from these studies, integration of PV panels with green roof systems may improve the performance for both. The benefits of this combination depend on multiple factors such as weather conditions and the characteristics of the vegetation system (plant type, soil type/depth, and irrigation). However, despite this empirical evidence, there are potentially two competing mechanisms that may affect system performance that have not been studied in depth. While vegetation may provide a benefit by reducing the net radiation load on the underside of the PV panels, it may produce a negative effect inhibiting airflow and thus reducing the convective cooling of the PV panels. There is a gap in the literature comparing these competing effects. The present study aims to fill this gap by investigating two questions: How does the underlying roof type affect the performance of a roof-integrated PV system? And how is PV panel temperature and performance affected by the height of the PV panel above the roof? This latter question has two parts:

How does the PV panel heat transfer coefficient (*h*) vary with the PV panel height, and does the vegetation of a green roof reduce the convective cooling of the PV panels?

Chapter 2: Methodology

2.1. Test Facility

The experiments were performed over a two-month period from July 18 to September 15, 2014 on the roof of the Science Research and Teaching Center (SRTC) Building at Portland State University (PSU), Portland, Oregon, United states, at latitude 45.52˚ N and longitude 122.68˚ W. On this roof, PSU had previously established the Green Roof Integrated with Photovoltaics (GRIPV) project. The objective of GRIPV is to investigate the benefits of combining the green roof with photovoltaic panels. The GRIPV test roof contains seven PV panel arrays, each with four SolarWorld 175 Watt photovoltaic modules. Five arrays are above dedicated long-term green roof experiments, whereas two arrays are on a Thermo-Plastic Polyolefin (TPO) membrane conventional roof. The dimensions of each PV panel are 0.8 m by 1.6 m and all the panels are facing south. Within each array, the space between panels is 0.3 m. The lower edge of each panel is 0.18 m above the roof, and the tilt angle is 30˚ from the horizontal. Each panel has its own Enhance M210 Microinverter. The maximum power output from this inverter is 210 watt [58]. Two identical panels on the conventional roof were used for all measurements in this research. As needed, the surfaces were modified to simulate PV placement above green, white, or black roofing. Figure 2.1 shows the Portland State University test facility on the roof of the STRC Building. The view is from the west looking east.

Figure 2.1: The Portland State University GRIPV test facility on the roof of STRC Building.

2.2. Experiment layout

Three types of roofing were used in the experiments to investigate the effect of underlying roof type on the performance on a roof integrated PV system. Roof types studied were black and white membranes, and vegetated green roofs. The type of black and white roofs is Ethylene Propylene Diene Monomer (EPDM). The green roof used Dianthus (a herbaceous perennial) planted in a soil that was approximately 0.06 m thick. The size of each roof test area was (2.2 m by 3 m) to ensure that the test treatments were the dominant surface interacting with the corresponding PV panel.

Radiative properties of samples of these roof materials were measured using a spectrophotometer for albedo and a reflectometer for long-wave emissivity. Three samples were taken for black and white roofs to measure their emissivity and albedo. The black membrane had an albedo of 0.06 and an emissivity of 0.91. The albedo and the emissivity of the white roof were 0.64 and 0.88, respectively. Five samples of the dianthus were taken to measure the emissivity and the albedo in order to get accurate values for these properties. The albedo and the emissivity of the dianthus were 0.28 and 0.95, respectively. The radiative properties of black and white membranes which were used in the tests were very similar to the properties of the black and white membrane (EPDM) presented by Lawrence Berkeley National Laboratory in their “Cool Roofing Material Database” [59].

To study the effect of the height of the PV panel on the heat transfer coefficient, the experiments were conducted at two heights (18 cm and 24 cm), both measured as the spacing between the roof surface and the lower edge of the PV panel. While the preferable experimental arrangement would involve a single experiment in which all three surfaces are simultaneously tested side by side, limitations in the available sensors and monitoring equipment required conducting experiments involving two test surfaces at a time. To facilitate switching of roof treatments and alteration of panel heights all testing for this study used two PV panels located in arrays above the conventional roofing. Each roof test area was centered under one of the two test panels, and the two test panels were separated from each other by a third (unused) panel—a distance of 2.2 m. Thus, three experiments were performed at each height with pairs of test surfaces: green and black; green and white; and white and black. Figure 2.2 presents the layout of the experiments.

(a)

(b)

(c)

Figure 2.2: The experiments layout: (a) Green and Black surfaces, (b) Green and White surfaces, (c) White and Black surfaces.

2.3. Instrumentation

Temperatures of the underside of each PV panel surface were measured using averaged values from three K-type thermocouples with accuracy of ± 0.5˚C; one of the thermocouples was located approximately in the middle of the panel and the others were 0.5 m below and above the middle of the panel. The convective heat flux on the underside of the PV panel was measured using the average of two thin film heat flux sensors. The positions of these sensors were approximately in the center point of the PV panel and (0.5 m) below the center point. The air temperature between the PV panel and the roof surface was measured using a single thermocouple located approximately 0.27 m below the center point of the panel. These measurements enabled calculation of the PV panel convective heat transfer coefficient. Roof surface temperatures were measured using an average of readings from two T-type thermocouples located approximately under the middle of each panel, separated by a distance of 0.35 m. In the case of the green roof these sensors were placed less than 0.5 cm below the soil surface. The accuracy of the T-type thermocouple is ± 0.5˚C. The wind velocity under the PV panel was measured using two orthogonally-placed hot film anemometers located 0.18 m under the center point of the PV panel. These sensors were connected to a Campbell CR1000 datalogger. These sensors were all sampled at a frequency of 5 seconds and 15-minute averages were stored for analysis. The DC voltage, DC current and AC power of each panel were measured using an individual inverter placed on the underside of the module. Inverter data were recorded each minute. Figure 2.3 shows a side view of the PV panel above the green roof with the locations of the installed sensors.

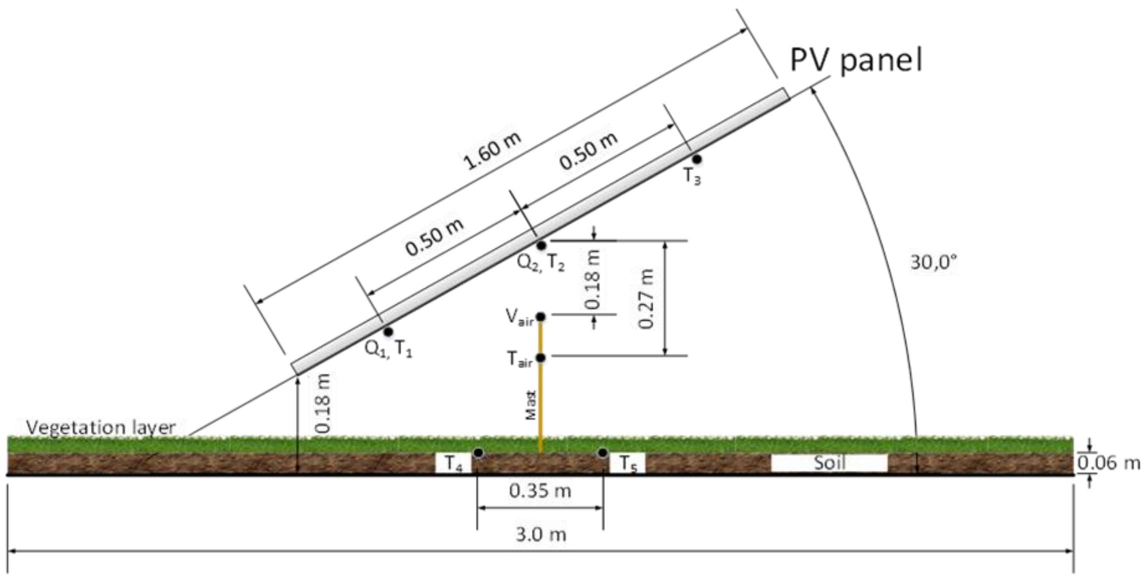


Figure 2.3: Cross sectional view of the PV panel above the green roof showing the positions of the sensors.

2.4. Experiment Design

The experiments were conducted over two months from July 18 to September 15, 2014. Two panels were employed in these experiments. Each experiment had a duration of at least three days. As noted above, three experiments were conducted at each height; each involving a pair of surfaces. Sequential testing of multiple test conditions was done using the same panel in comparison with a panel above the conventional roof which is a white TPO (ThermPlastic Polyoefin) membrane as a reference. This method was not helpful for comparisons of the PV panel above two different surfaces because it was difficult to find the same weather conditions for three days. However, this method was helpful to make an indirect comparison between the performances of the PV panel at two heights using the same roof. Weather data at 2 m height, including wind speed and direction, ambient temperature, rainfall, humidity, insolation (direct and reflected) and barometric pressure were obtained from a local weather station located at the same roof as the experiment. Because of these circumstances, we ran simultaneous testing of multiple test conditions using pairs of roofs at each test. The experiments were set up in this way so that we could make a direct comparison of PV panel performance for differing surface treatments under identical weather conditions.

Prior to initiation of the side-by-side comparison experiments, it was crucial to first establish that the two PV panel systems used in these tests had similar performance characteristics when exposed to identical conditions (including underlying roof surface treatments). Therefore we conducted measurements of PV panel surface temperatures and power output for the two test panels under identical conditions and roof treatments (existing conventional membrane roof) for a test period of three days. The panels on the roof of the SRTC Building are labeled A, B, C and D. As shown in Figure 2.4, panels A and C were chosen for these experiments to prevent the overlapping effect of the surfaces. The distance between panel A and C is 2.2 m.

Figure 2.4: Control test on panel A and C.

Chapter 3: Results

The results of this study are presented below. The first component of the experimentation involved control measurements to verify that the PV panel output performance of our two test panels was the same under identical conditions. The remaining experiments compare PV panel temperatures, convection coefficients, and power output for paired testing of differing roof treatments—green-black, green-white, and white-black at two heights.

3.1. Analysis method

The heat transfer coefficient was calculated using Newton's Law of Cooling:

$$h = \frac{q}{(T_P - T_a)} \tag{2}$$

Here, q represents the average convective heat flux that was measured on the backside of the PV panel by two sensors, T_P is the average of the PV panel temperature that was measured on the underside of the PV panel surface and, T_a is the ambient temperature under the PV panel. The distance between the ambient temperature sensor and the underside of the PV panel was 0.27 m.

The velocity magnitude was calculated from measurements from two orthogonally placed hot film anemometers:

$$u = \sqrt{u_x^2 + u_y^2} \tag{3}$$

The distance between the wind velocity seniors and the underside of the PV panel was 0.18 m.

3.2. Control Test Results

This experiment was performed at 18 cm height to evaluate the inter-panel performance variations under identical test conditions. Both test panels under these identical conditions were operating for three days above the conventional roof with a TPO membrane. Table 1 shows the results of the control test, including the mean value of each parameter and the standard deviation of each value. The PV panel temperatures, heat transfer coefficients, the wind velocity, and the power output were averaged hourly from the period of 10:00 am to 6:00 pm. This period was chosen to avoid the confounding effects of shading on the PV panels associated with nearby buildings and trees to the east and the west when the sun is low in the sky. As shown in Figure 3.1, the hourly temperatures of panels A and C at the control test were approximately similar. Based on these results, it is reasonable to claim that the two systems perform similarly under the same conditions.

Table 1. Summary statistics for the control test at 18 cm height.

Parameters	**Panel A**		**Panel C**	
---	Average	Std.Dev.	Average	Std.Dev.
h (W/m² ˚C)	10.9	2.86	10.8	2.54
Power (W)	89.6	22.5	89.5	22.5
Panel Temp. (˚C)	41.0	6.3	41.1	6.3
Velocity under panel (m/s)	0.31	0.09	0.30	0.09

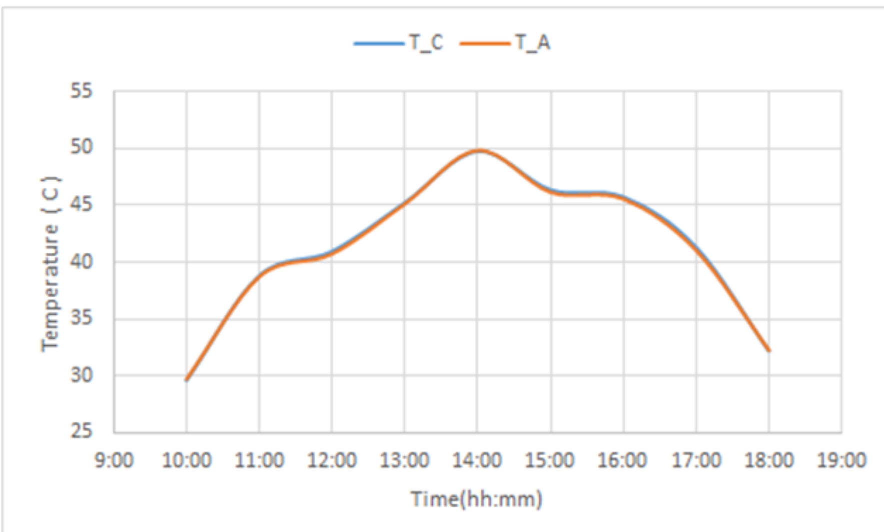


Figure 3.1: Hourly mean surface temperature for the panel A (T_A) and the panel C (T_C) at the control test.

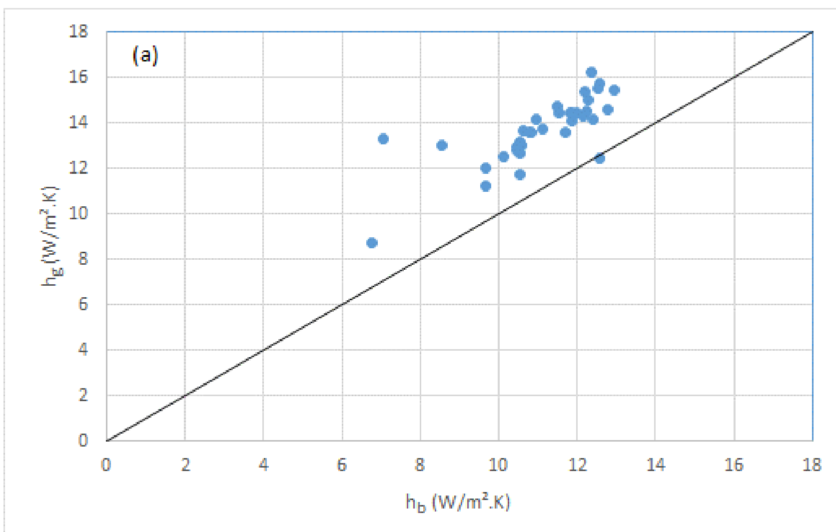
3.3. Comparison of Roof Treatments at 18 cm Height

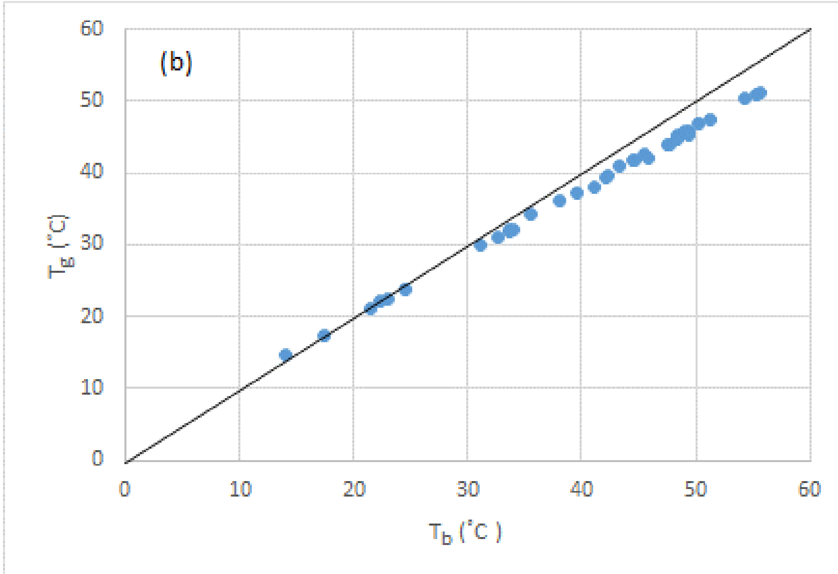
As mentioned previously, only two test surfaces could be tested at a time. Therefore, the following subsections present the results of each experiment (pairs of surfaces) separately, as tested at a PV panel height of 18cm.

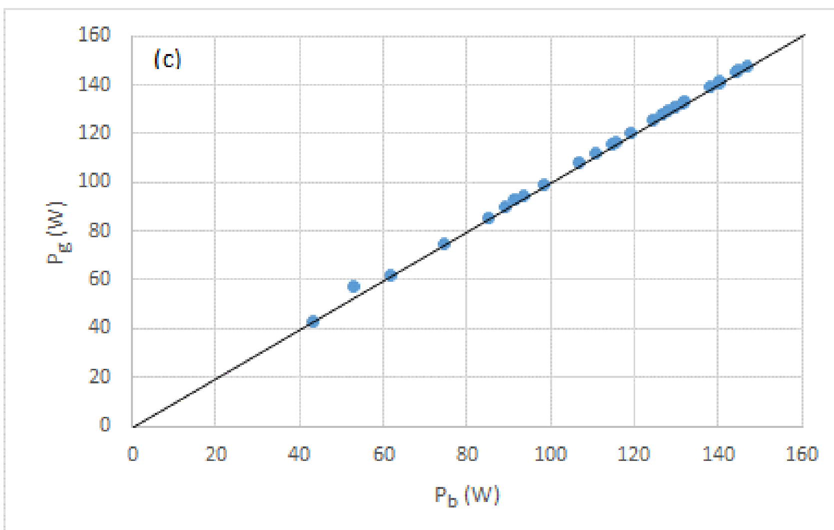
3.3.1. Green vs. Black Roof at 18 cm

The comparison test of the PV panel (panel A) above the green and the PV panel (panel C) above the black roof showed that the hourly mean soil surface temperature for the green roof system was 15˚C lower than the mean temperature of the black surface during the day (10:00 am to 6:00pm). As a result of the modified radiation energy exchange, one would expect the PV panel above the green roof to be cooler than the one above the black roof. The vegetation, however, also appears to have a significant effect on the local mixing under the PV panel, enhancing the convection coefficient as illustrated in Figure 3.2a. The mean heat transfer coefficient of the PV panel surface above the green roof was 23% higher than that above the black roof, despite nominally similar local air velocities. This effect would serve to further cool the PV panel above the green roof, as the ambient air temperature during the day was consistently lower than the panel surface temperatures. The net result of this modification to the panel energy balance is that the PV panel above the green roof was 2.5˚C cooler than that above the black roof. Figure 3.2b illustrates this panel cooling effect in a comparison plot of the PV panel temperatures during the experiment. As a result of the cooler panel surface temperature, the PV panel above the green roof generated 1.16% more electricity than the PV above the black roof—a nominal sensitivity of 0.46%/˚C. The results of the power output differences between the PV-green roof and the PV-black roof were statistically significant at the 95% confidence interval ($P < 0.001$). A comparison of power output from the panel above the green and black roofs is given in Figure 3.2c.

Figure 3.2: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the green-black roof experiment at a height spacing of 18 cm.



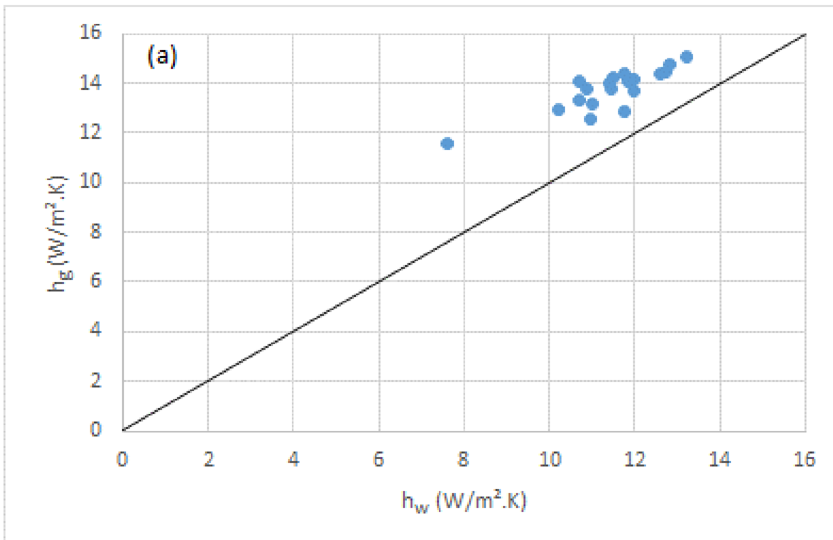

(b)
T_g (˚C)
T_b (˚C)
0
10
20
30
40
50
60

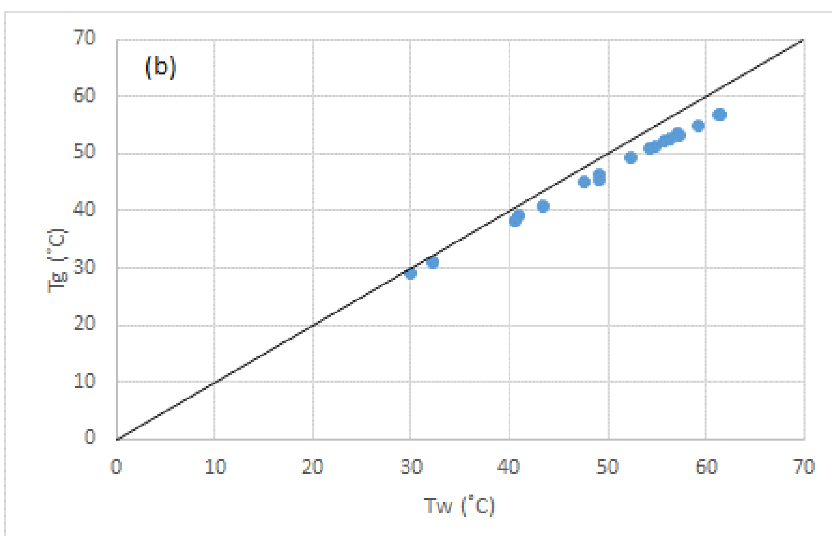

(c)
P_g (W)
P_b (W)
0
20
40
60
80
100
120
140
160

3.3.2. Green vs. White Roof at 18 cm

The results of the PV panel (panel A) above the green roof and the PV panel (panel C) above the white roof showed that the hourly mean temperature of the panel surface above the green roof was 3.0˚C lower than the temperature of the panel surface above the white roof as illustrate in Figure 3.3b. The hourly mean soil surface temperature was 14˚C lower than the temperature of the white surface. Despite the high albedo of the white roof, the temperature of the PV-green roof was lower due to the effect of the evapotranspiration from the soil and plants. In addition, the temperature of the soil surface was lower than the white roof surface and the emissivity of the green roof was higher than the emissivity of the white roof. As illustrated in Figure 3.3a, the hourly mean heat transfer coefficient for the PV panel surface above the green roof was 20% higher than that of the PV panel surface above the white roof during the period of the test. The high heat transfer coefficient of the PV-green roof was due to the roughness of the green roof, which was higher than that of the white roof. The PV panel above the green roof produced about 0.75% more power output than the PV panel above the white roof as shown in Figure 3.3c. The results of the power output differences between the PV-green roof and the PV-white roof were statistically significant at the 95% confidence interval ($P < 0.001$). It is noticeable there was a difference in the power output of the PV panels above the green vs. white roofs, and in the power output of the PV panels above the green vs. the black roofs. This difference was due to the different climate conditions between the periods of the experiments. Table 2 shows the results (the mean value and standard deviation (σ)) of the PV above the green roof in comparison with the PV panel above the white and the black roofs at 18 cm height.

Figure 3.3: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the green-white roof experiment at a height spacing of 18 cm.





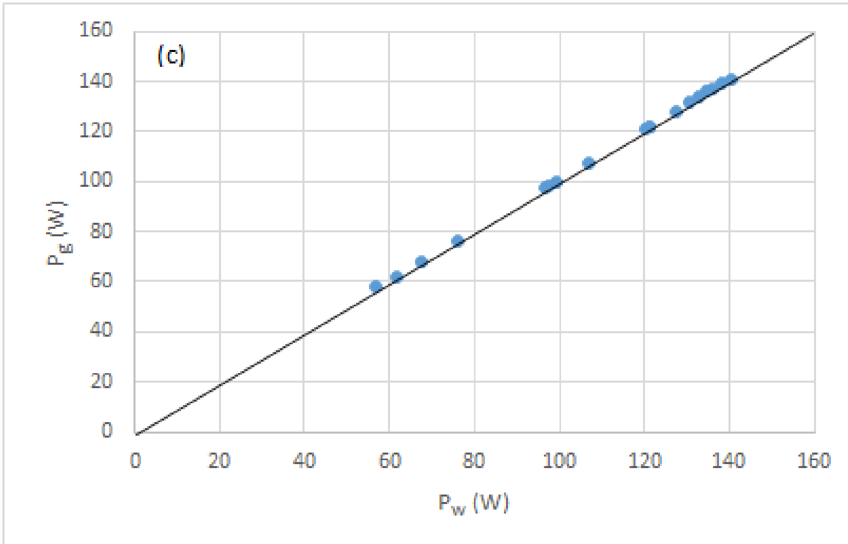


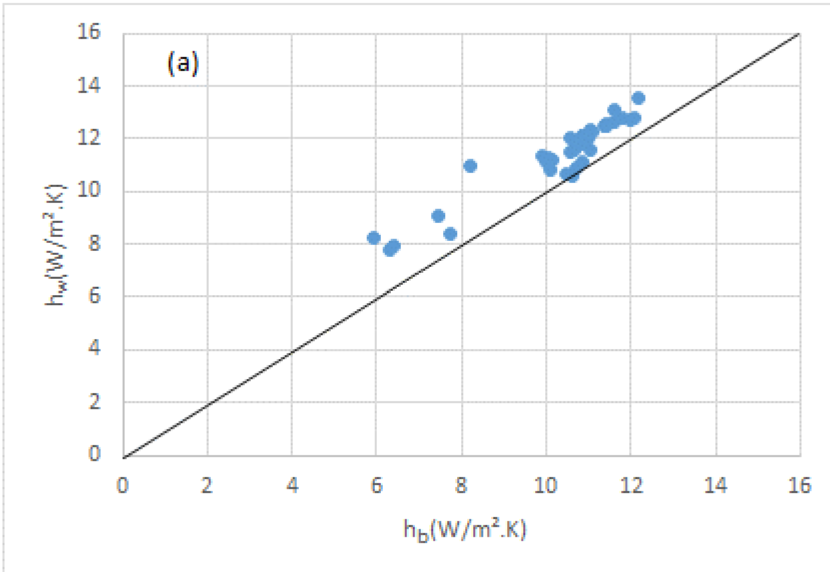
Table 2. The results of the PV-green roof in comparison to the PV panel above the white and the black roofs at 18 cm height.

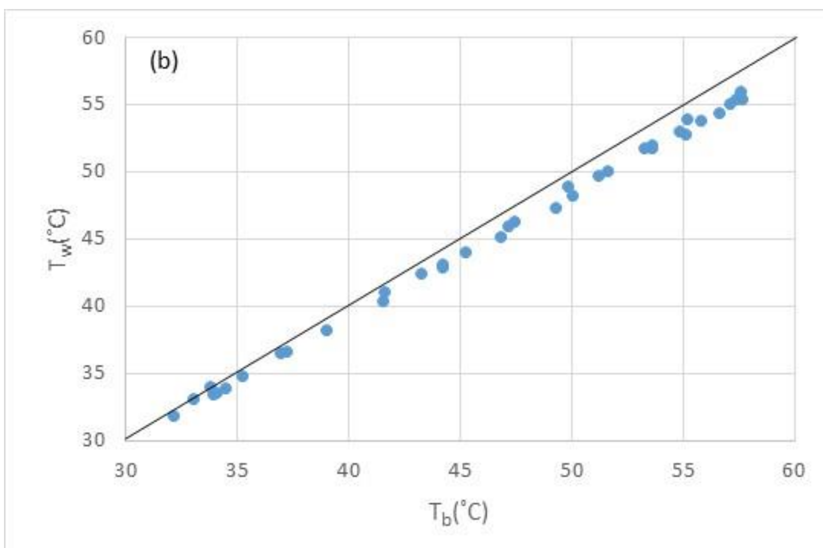
Parameters	**PV-green-white roof**		**PV-white roof**		**PV-green-black roof**		**PV-black roof**	
---	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Power (W)	109.75	29.0	108.93	29.0	106.82	32.0	105.59	32.0
PV-Temp. (˚C)	47.0	8.4	50.1	9.4	37.76	8.86	40.27	10.0
h (W/m².˚C)	13.80	0.86	11.50	1.23	13.68	1.45	11.10	1.47

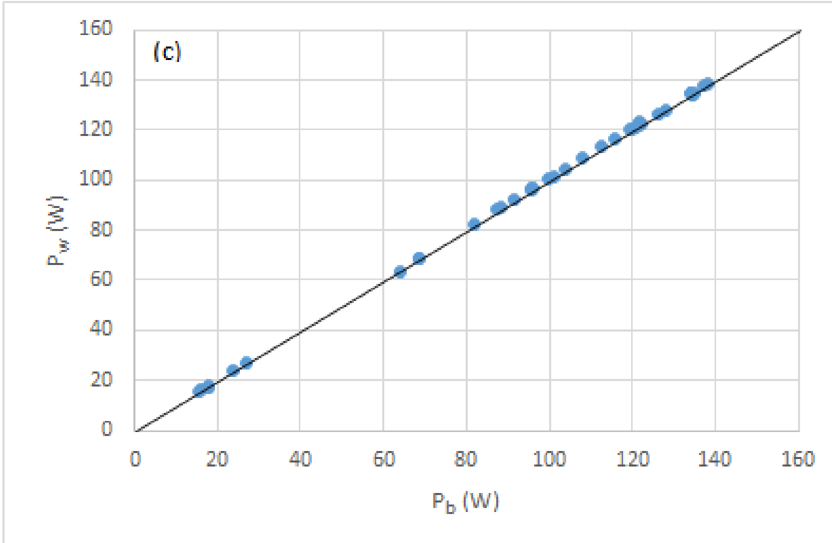
3.3.3. Black vs. White Roof at 18 cm

In the experiment of the PV panel (panel C) above the black roof and PV panel (panel A) above the white roof at 18 cm height, the results showed the hourly mean temperature of the PV panel surface above the white roof was 1.3˚C lower than the PV panel surface above the black roof. Figure 3.4b shows the hourly average temperature of the PV-white roof vs. the PV-black roof. The hourly mean temperature of the white roof surface was 3.3˚C lower than the black roof surface due to the high albedo of the white roof, so it keeps the white roof surface cooler. The hourly mean heat transfer coefficient (*h*) of the PV-white roof (11.0 $W/m^2.C$) was 6.7% higher than that of the PV-black roof (10.3 $W/m^2.C$), Figure 3.4a. The hourly mean power output of the PV-white roof and the PV-black roof were 99.2 W and 98.5 W, respectively. As illustrated in Figure 3.4c, the PV-white roof generated 0.7% more electricity than the PV-black roof during the test period. The results of the power output differences between the PV-white roof and the PV-black roof were statistically significant at a 95% confidence interval ($P < 0.001$).

Figure 3.4: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the white-black roof experiment at a height spacing of 18 cm.







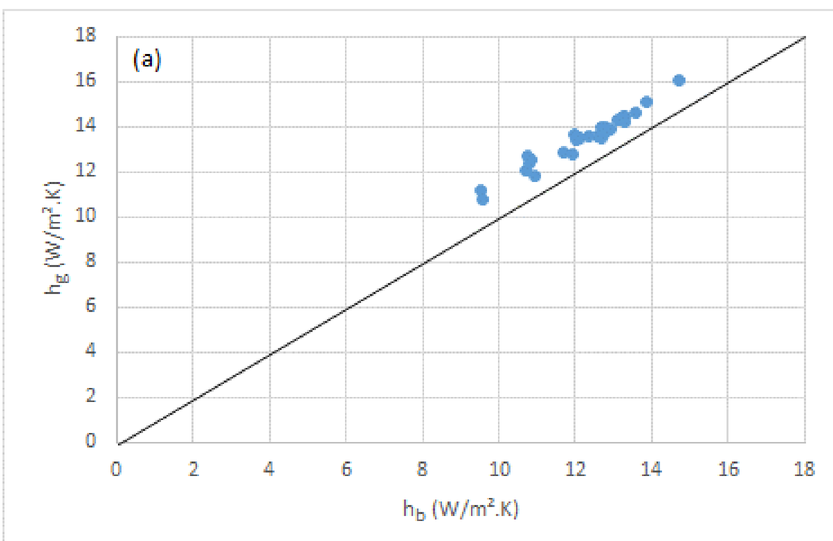
3.4. Comparison of Roof Treatments at 24 cm Height

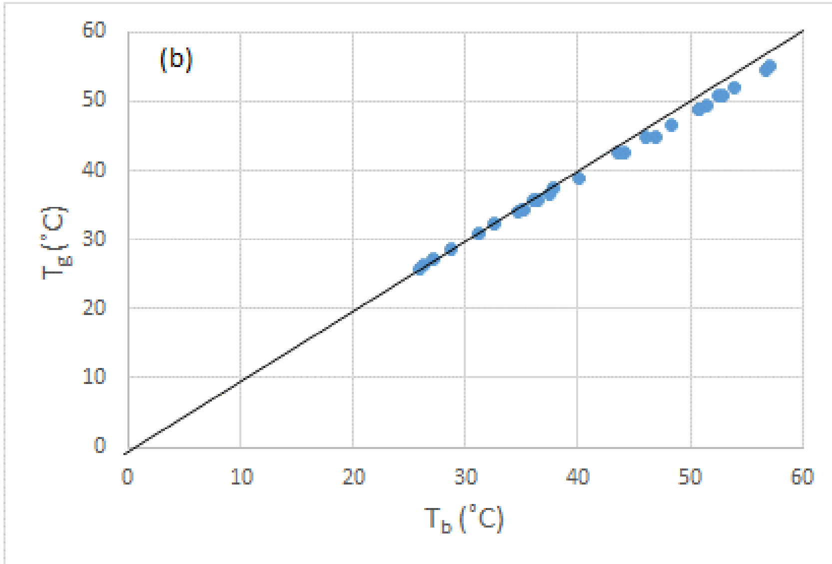
An additional set of experiments was performed at a panel height of 24 cm. The intent was to evaluate how panel vertical spacing affected the relative performance of the different roof treatments. Since the experimental panels were physically connected by a fixed structural support system, it was not possible to make a direct comparison of performance of a system at two different heights under identical conditions. This section simply presents the results from the 24 cm height in a parallel fashion to the presentation in section 3.3 for the 18 cm height. Section 3.5 then attempts to make an indirect comparison between the two heights to assess the role of height in affecting PV performance.

3.4.1. Green vs. Black roof at 24 cm

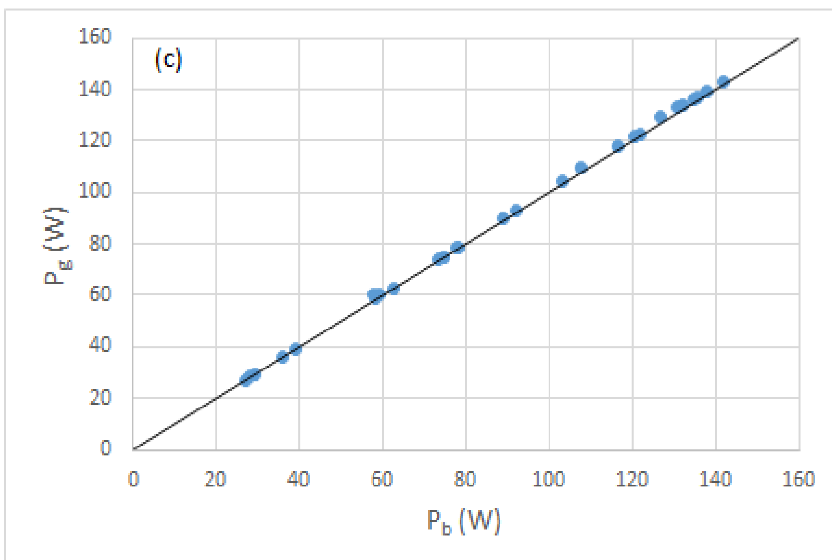
In the experiment of the PV panel (panel A) above the green roof with the PV panel (panel C) above the black roof at 24 cm height, the results showed that the hourly average of the soil surface temperature was 14.8˚C lower than the temperature of the black roof surface. The hourly mean heat transfer coefficient of the PV-green roof was 10.2% higher than the value for the PV-black roof (Figure 3.5a). As a result, the hourly mean temperature of the panel above the green roof was 1.8˚C cooler than that above the black roof (Figure 3.5b). The corresponding impact on power output was that the PV panel above the green roof had 1% higher output than that of the PV above the black roof (Figure 3.5c). The results of the power output differences between the PV-green roof and the PV-black roof were statistically significant at the 95% confidence interval ($P < 0.001$).

Figure 3.5: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the green-black roof experiment at a height spacing of 24 cm.





(b)
0
10
20
30
40
50
60
T_g (°C)
T_b (°C)



(c)
0
20
40
60
80
100
120
140
160
P_g (W)
P_b (W)

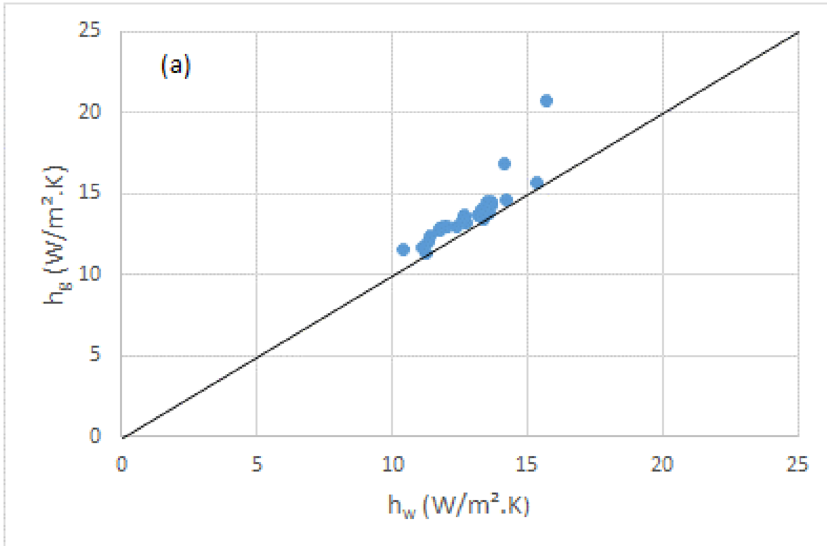
3.4.2. Green vs. White Roof at 24 cm

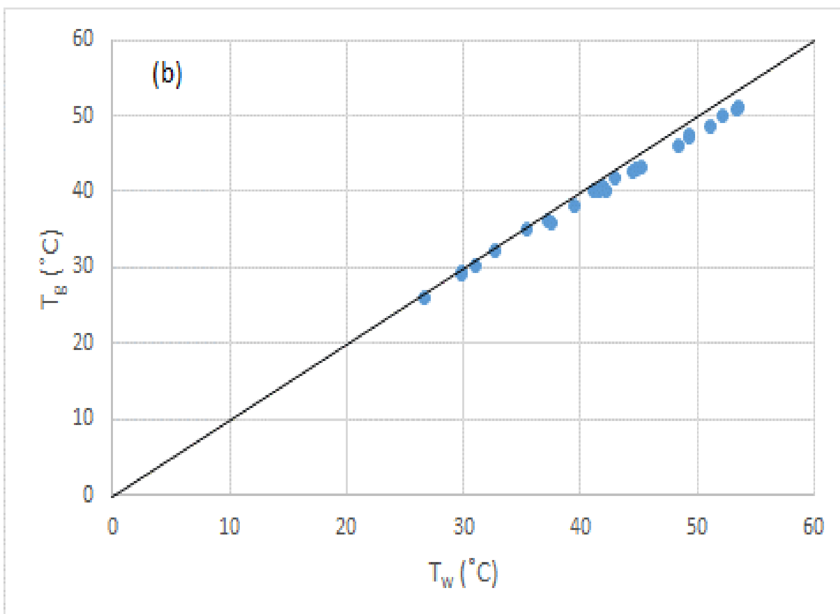
The results of the experiment of the PV panel (panel A) above the green roof with the PV panel (panel C) above the white roof at 24 cm height showed that the hourly mean soil surface temperature for the green roof system was 13.5˚C cooler than the temperature of the white roof surface. The hourly mean heat transfer coefficient of the PV-green roof was 7% higher than that for the PV-white roof (Figure 3.6a). As a result, the hourly mean temperature of the PV-green roof was 1.5˚C cooler than the PV-white roof (as illustrated in Figure 3.6b). The hourly mean power output of the PV-green roof was 0.68% higher than the power output of the PV-white roof (Figure 3.6c). The results of the power output differences between the PV-green roof and the PV-white roof were statistically significant at a 95% confidence interval ($P < 0.001$). Table 3 shows the results of the PV-green roof vs. the PV-white roof and the PV-green roof vs. the PV-black roof at 24 cm height.

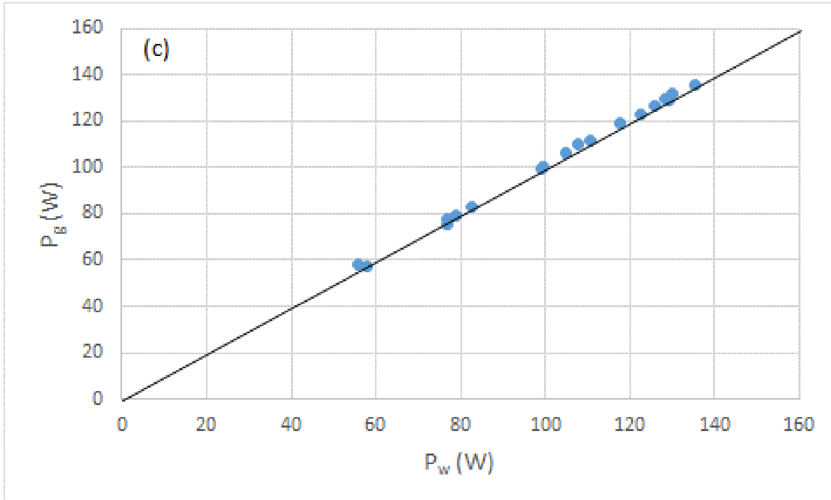
Table 3. Results of the PV-green roof vs. the PV-white roof and the PV-green roof vs. the PV-black roof at 24 cm height.

Parameters	**PV-green roof-white**		**PV- white roof**		**PV-green roof-black**		**PV-black roof**	
---	mean	σ	mean	σ	mean	σ	mean	σ
Power (W)	103.0	23.5	102.3	23.2	89.5	24.8	88.6	24.5
h (W/m².C)	13.75	1.86	12.84	1.30	13.60	1.5	12.34	1.5
PV-Temp. (C)	40.0	6.6	41.5	7.2	40.4	5.9	42.2	6.5

Figure 3.6: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the green-white roof experiment at a height spacing of 24 cm.



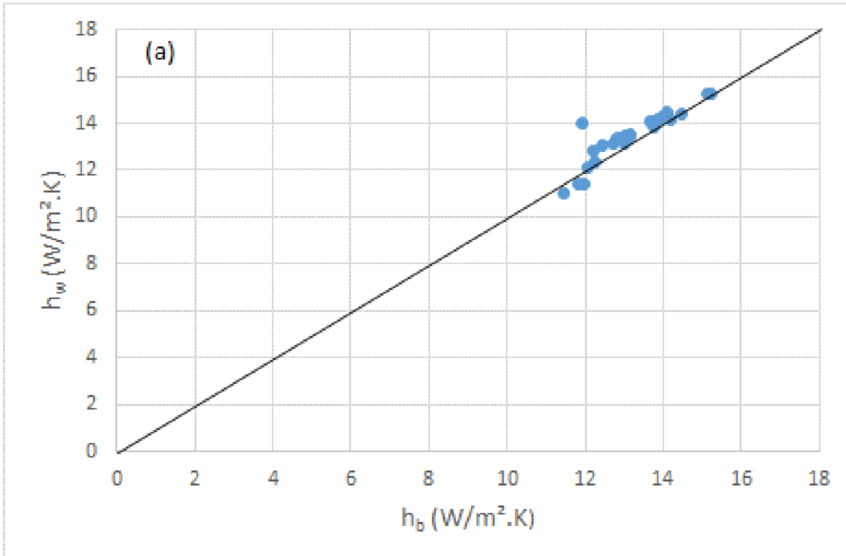


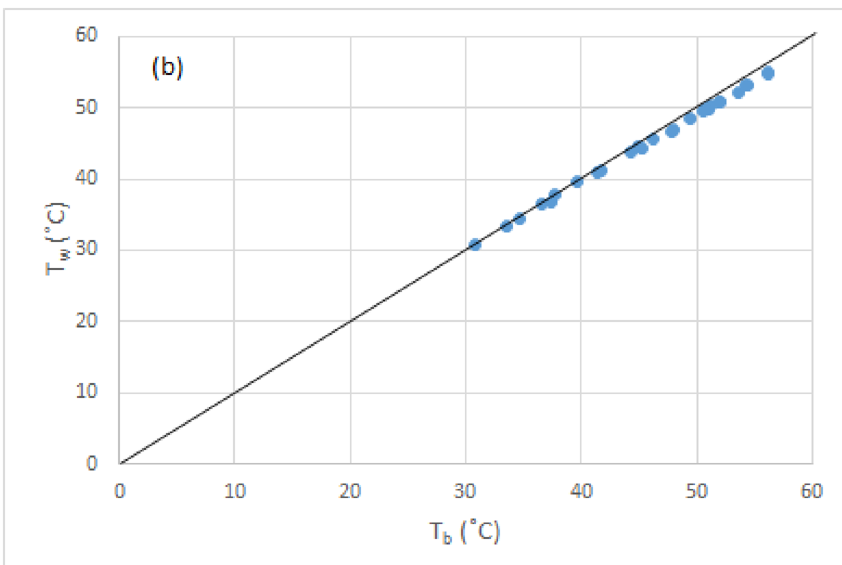


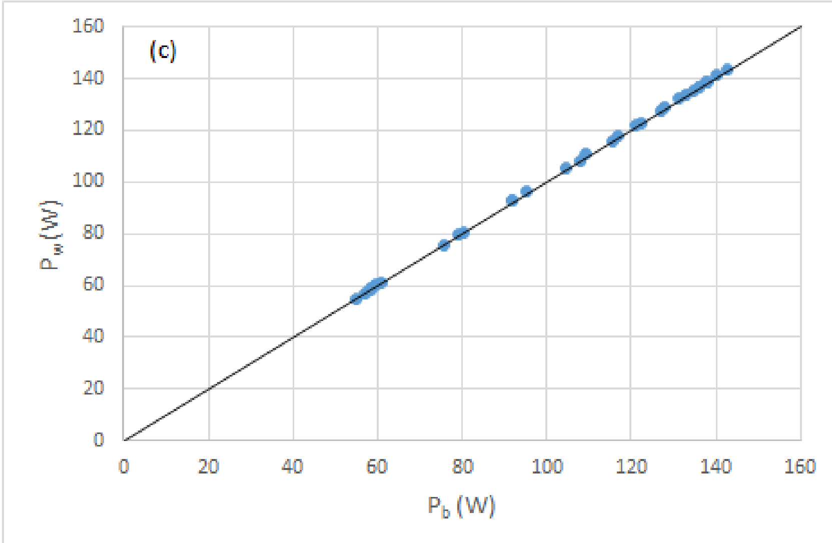
3.4.3. White vs. Black Roofs at 24 cm

In the experiment of the PV panel (panel A) above the white roof vs. the PV panel (panel C) above the black roof at 24 cm height, the results showed the hourly mean temperature of the white roof surface was 3.4˚C lower (34.2˚C vs. 37.6˚C) than the black roof surface during the day light hours of this test. The hourly mean heat transfer coefficient of the PV-white roof was 2.0% higher (13.41 ($W/m^2.K$) vs. 13.15 ($W/m^2.K$)) than that of the PV-black roof as illustrated in Figure 3.7a. The hourly mean temperature of the PV-white roof was 0.8˚C cooler (45.2˚C vs. 46.0˚C) than the PV-black roof (Figure 3.7b). The mean power output of the PV-white roof was 0.44% higher (103.80 vs. 103.35 W) than the power output of the PV-black roof. The results of the power output differences between the PV-white roof and the PV-black roof were statistically significant at the 95% confidence interval ($P < 0.01$). Figure 3.7c shows the power output of the PV-white roof vs. PV-black roof.

Figure 3.7: Comparison of panel surface (a) convection coefficients, (b) temperatures, and (c) power output during the white-black roof experiment at a height spacing of 24 cm.







3.5. Evaluating the Role of PV Panel Height

While the side-by-side experiments discussed in sections 3.3-3.4 allow direct comparison of different roof treatments under identical weather conditions, due to structural constraints, we were not able to simultaneously test panels at two different heights. Thus, we monitored panel performance first with both panels set to the 18 cm height (section 3.3) and then conducted the same experiments with the panels set at the 24 cm height (section 3.4). To compare performance associated with differing panel heights under similar weather conditions the GRIPV weather station was used as a reference to identify periods of similar weather during the two testing periods. This similarity was determined based on four weather parameters: ambient air temperature, wind direction, wind speed, and incident short-wave radiation. The specific days selected for the height intercomparisons are listed in Table 4 along with summary weather statistics (averaged every 15 minutes) used to justify their similarity. As we were unable to identify periods within the white roof experiments that represented similar conditions for the 18 cm and 24 cm experiments, only results from the green and black roof treatments (at both heights) are presented below. In the case of using the green roof under the PV panel, the weather conditions on Aug. 5 and Aug. 6, 2014 were approximately the same from 11:00 am to 5:00 pm. In the case of using the black roof, weather data on Aug. 2 and Aug. 25 were approximately similar from 10:00 am to 3:00 pm. As shown in Figure 3.7, the wind speed and its direction on Aug. 2 and Aug. 25 for the period mentioned above were approximately the same. It is significant to note that the wind directions fluctuate about their average values by approximately ±15˚ [60].

Table 4. Weather characteristics measured at the reference rooftop weather station for the comparison periods for green and black roofs at two different heights.

Parameters	**Green roof**		**Black roof**	
---	18 cm (Aug. 5)	24 cm (Aug. 6)	18 cm (Aug. 2)	24 cm (Aug. 25)
Ambient Temp. (˚C)	27.6	27.5	28.7	29.5
Wind speed (m/s)	0.78	0.84	0.80	0.85
Wind direction (degree)	210.0	226.0	234.0	232.0
Short wave rad. (W/m^2)	686.0	713.0	728.5	736.9

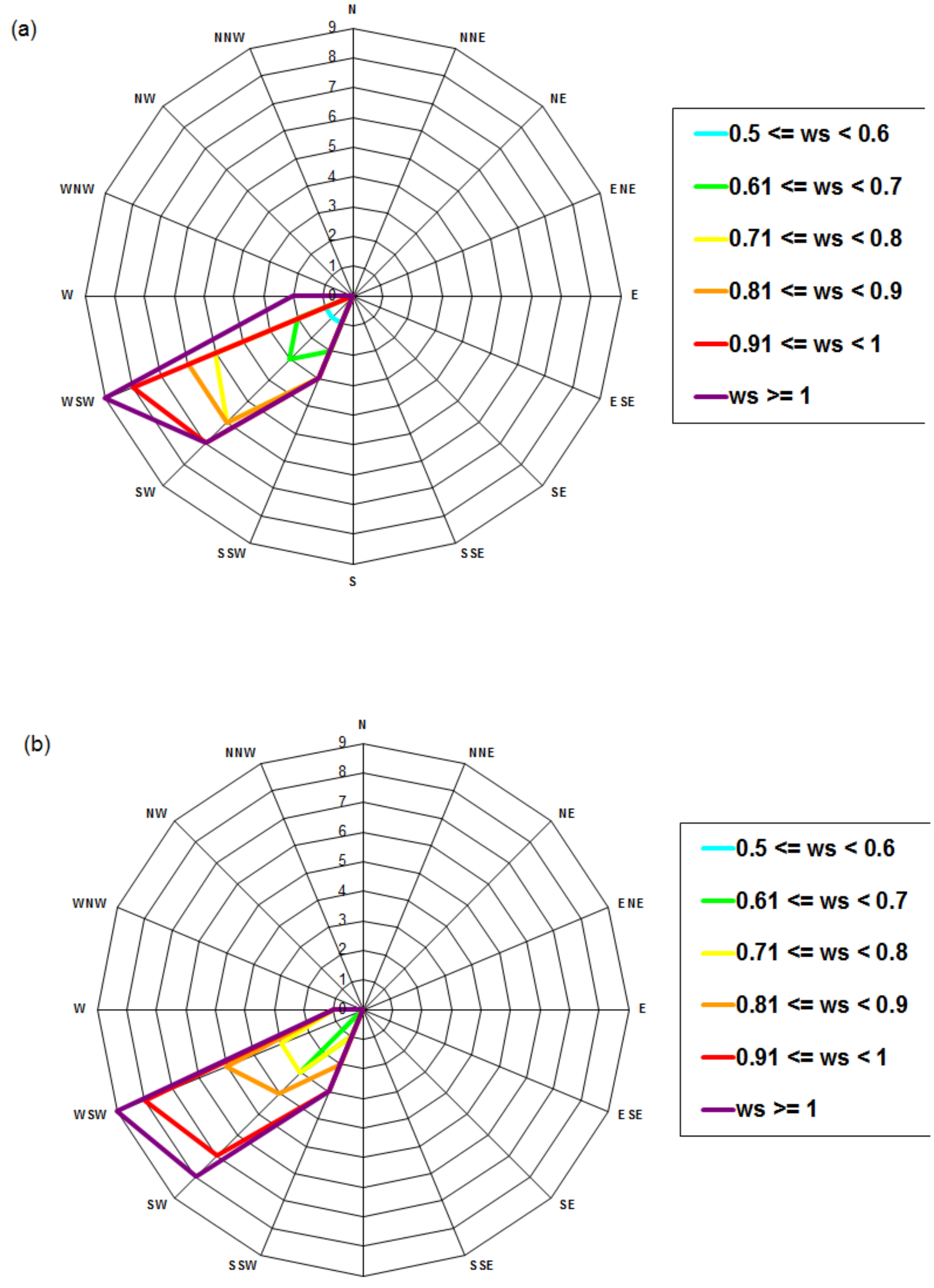


Figure 3.8: Wind rose shows the wind speed and its direction (a) Aug.2, (b) Aug.25, for the period from 10 am to 3 pm.

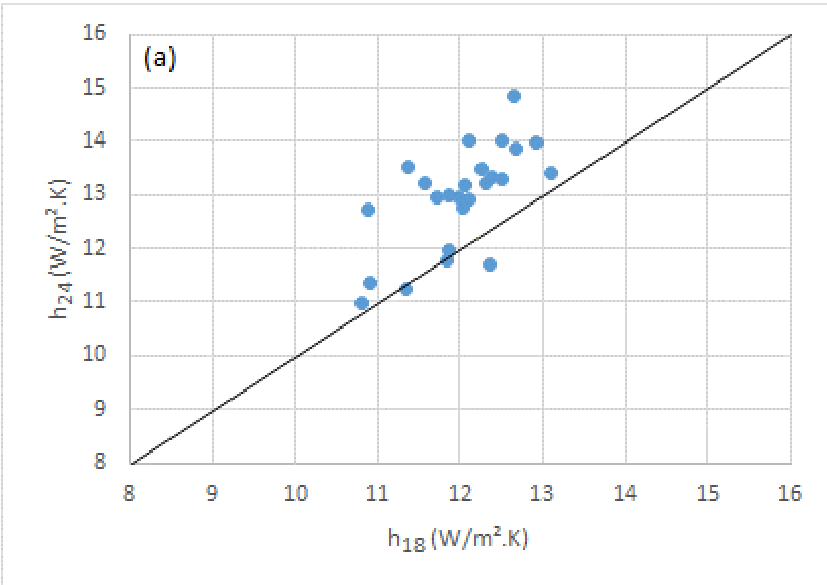
3.5.1. Green Roof at 18 and 24 cm

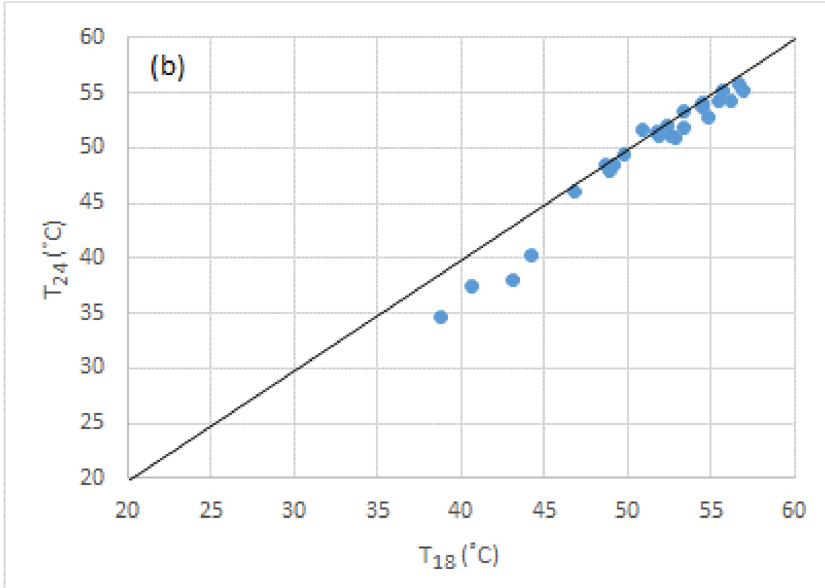
As the height of the panel was increased, airflow under the panel became less restricted: the mean wind speed under the 24 cm panel height was 0.45 m/s while it was only 0.32 m/s under the 18 cm panel. As a result, the mean heat transfer coefficient of the 24 cm height panel was greater by 8% as shown in Figure 3.9a. Another example to show the comparison between the convective coefficients at both heights is using the correlation between the heat transfer coefficient and the local wind speed, which was measured under the PV panel. Table 5 shows the linear regressions between the convective coefficients and the local wind speeds in the case of using the green roof under the PV panel. It is clear that the correlation of the 24 cm PV panel was higher than that of the 18 cm PV panel as shown in Figure 3.10. However, despite the general similarity of weather conditions during these two tests, the incoming solar radiation was 3.9% greater during the 24 cm height test. Furthermore, the 24 cm height case also had a panel surface temperature that was 1.4˚C cooler than the panel at the lower height (Figure 3.9b). With the nominal panel temperature sensitivity of 0.46%/˚C and the higher incident solar radiation, one might expect that the PV panel power production for the 24 cm height panel to be on the order of 4.5% greater. In fact, the mean power output at the 24 cm height was 4.8% greater than that of the 18 cm panel (Figure 3.9c). It must be emphasized that this was largely due to differences in available solar radiation. Nevertheless, the higher convection coefficients associated with the larger spacing resulted in lower panel surface temperatures and a performance increase of roughly 0.6%.

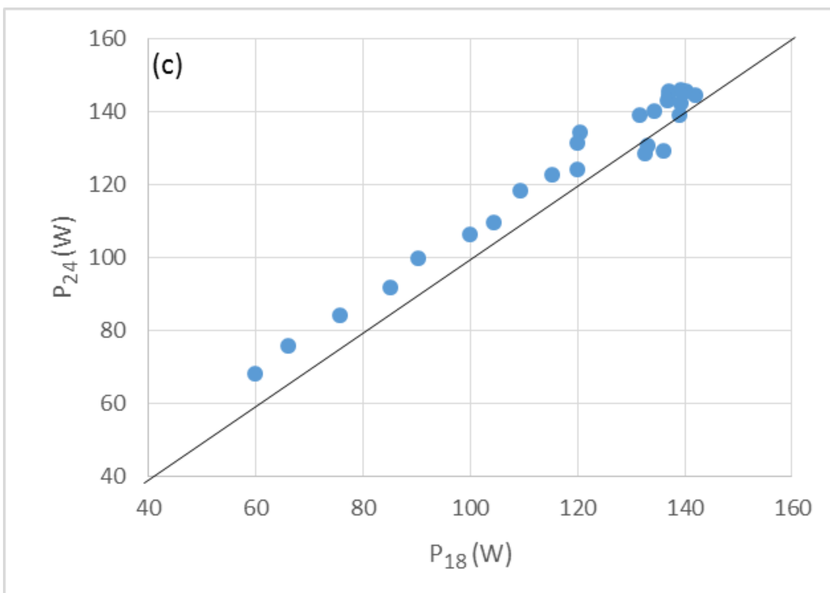
Table 5. Linear regressions between convective heat transfer coefficients and the local wind speeds at 18 cm and 24 cm heights for the PV-green roof.

Height (cm)	Correlation	R^2
18	$h = 4.65 * V + 10.44$	0.64
24	$h = 5.43 * V + 10.47$	0.61

Figure 3.9: Results for the (a) convection coefficients, (b) temperatures, and (c) power output of the PV panel above the green roof at 18 cm and 24 cm heights




(b)
T_{24} (°C)
T_{18} (°C)
20
25
30
35
40
45
50
55
60


(c)
P_{24} (W)
P_{18} (W)
40
60
80
100
120
140
160

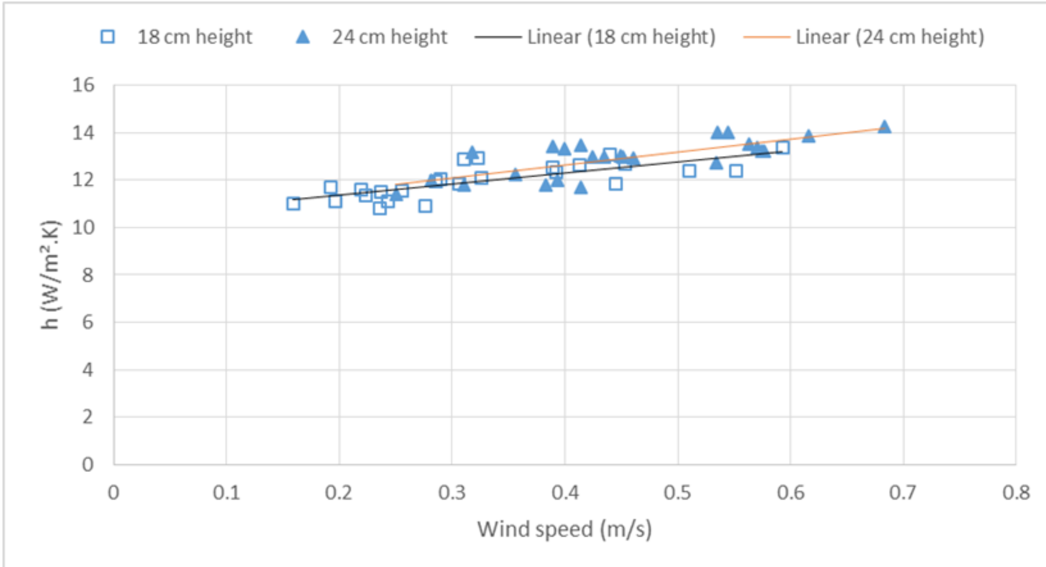


Figure 3.10: Comparison of convective coefficients between the 18 cm and 24 cm heights of the PV-green roof.

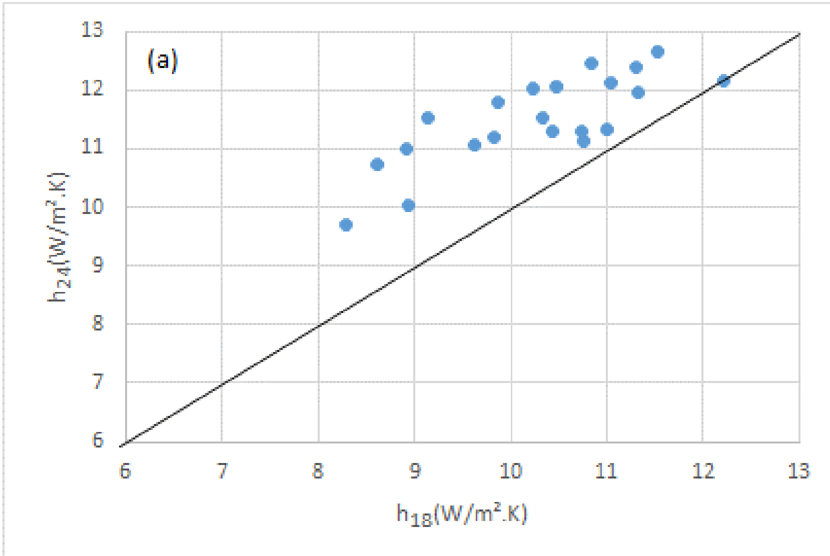
3.5.2. Black Roof at 18 and 24 cm

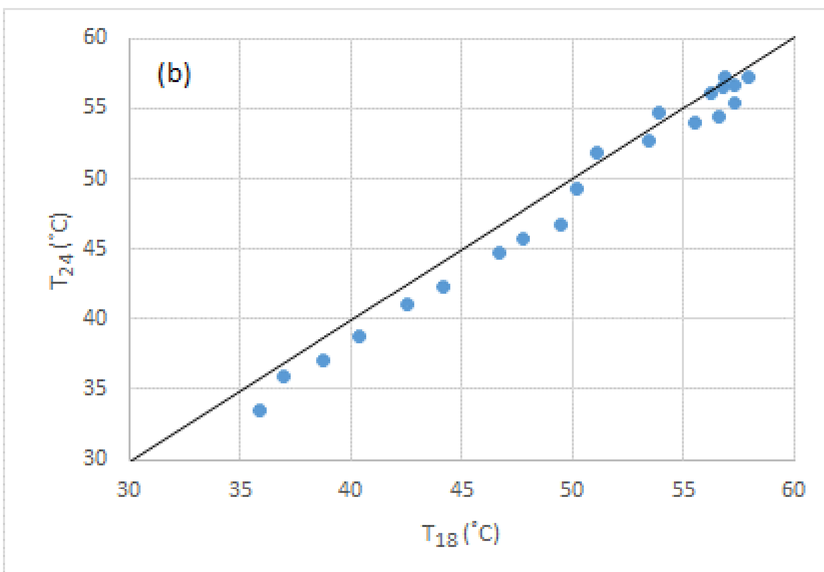
The comparison of the PV panel performance above a black roof at the two heights followed a similar pattern as the results for the green roof. Although the solar radiation was about 1% higher and the ambient temperature was 0.8˚C warmer during the 24 cm test, the panel actually had a surface temperature that was 1.2˚C cooler than the 18 cm panel (Figure 3.11b). Again, this was likely due to a higher convection coefficient in the 24 cm panel case. As with the green roof tests, raising the panel height above a black roof also increased flow velocities and convection coefficients. The mean wind speed under the 24 cm panel height was 0.50 m/s while it was only 0.34 m/s under the 18 cm panel. Specifically, the mean heat transfer coefficient of the 24 cm height panel was 12.2% greater than that of the 18 cm panel (Figure 3.11a). In addition, the correlation between the convective coefficient and the local wind speed, which was measured under the PV panel, was used to compare between the heat transfer coefficients and the local wind speeds at the 18 cm and 24 cm heights. Table 6 shows the linear regressions between the convective coefficients and the local wind speeds at 18 cm and 24 cm heights of the PV-black roof. The correlation of the 24 cm PV panel was higher than that of the 18 cm PV panel as shown in Figure 3.12. The mean power output of the 24 cm panel was 1.8% higher than for the 18 cm panel (Figure 3.11c). This is roughly the same as the 1.6% that we would expect simply factoring in the higher available solar radiation (1%) and accounting for the surface temperature sensitivity (1.2˚C * 0.46%/˚C). Again, it is important to reiterate that the performance improvement due to the increased panel height is just the ~0.6% improvement resulting from the 1.2˚C reduction in panel surface temperatures.

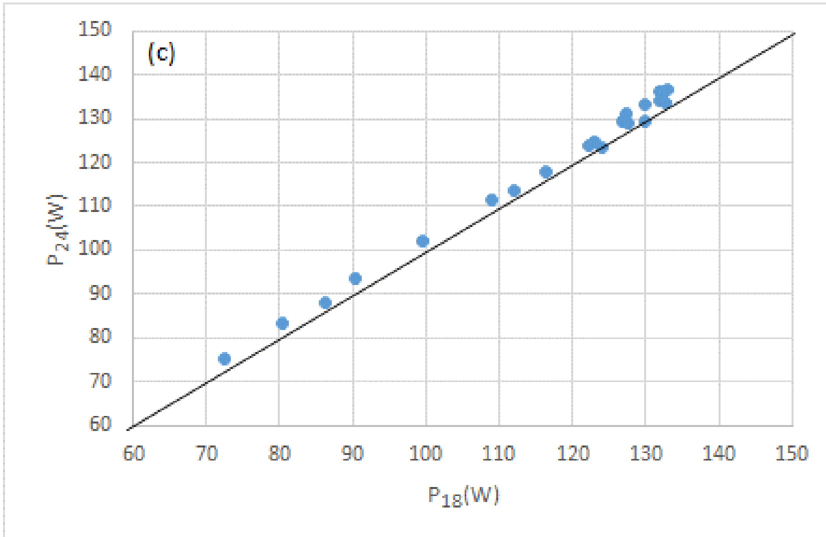
Table 6. Linear regressions between convective heat transfer coefficients and the local wind speeds at 18 cm and 24 cm heights for the PV-black roof.

Height (cm)	Correlation	R^2
18	$h = 5.27 * V + 8.57$	0.75
24	$h = 5.66 * V + 8.78$	0.78

Figure 3.11: Results for the (a) convection coefficients, (b) temperatures, and (c) power output of the PV panel above the black roof at 18 cm and 24 cm heights.







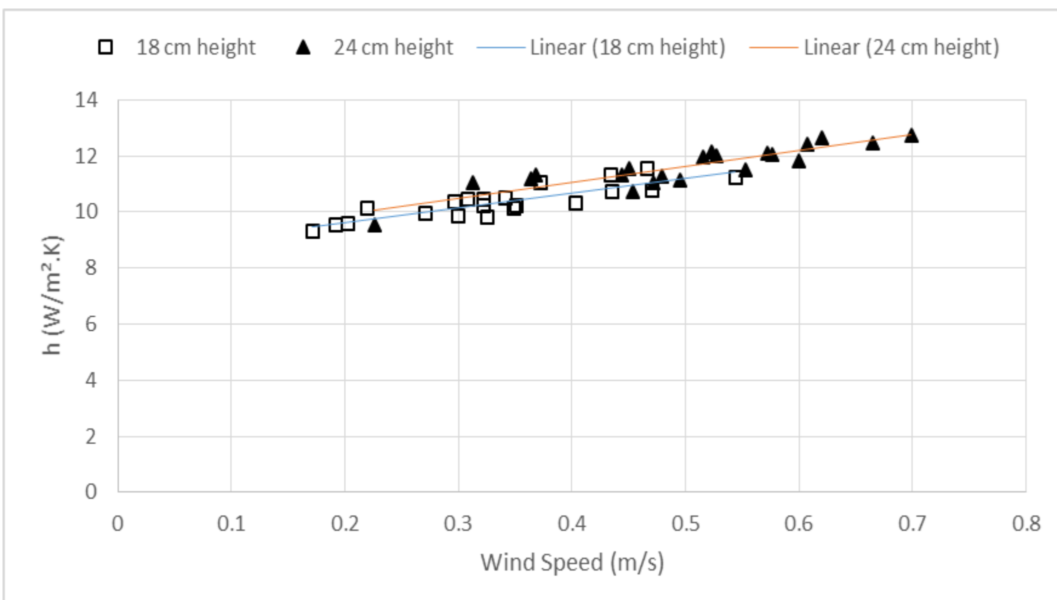


Figure 3.12: Comparison of convective coefficients between the 18 cm and 24 cm heights of the PV-green roof.

3.6. Comparing this study with prior studies

Considering the experimental studies noted in the introduction, it is valuable to make a comparison between this study and some of the previous experimental studies.

In the case of the study presented by Nagengast et al. [55], the results of the data collected from a large field project in Pittsburgh, Pennsylvania showed that the mean power output of the PV panels above the green roof was 0.5% higher than the power output of the PV panels above the black roof, which was EPDM, in June 2012. Moreover, in the same study, the results showed that the PV-green roof outperformed the PV-black roof by 0.9% when the ambient temperature was higher than 25˚C in May, June, and July. Regression equations were derived from the study's data and used to estimate the difference in the PVs power output from black and green roofs in other climates. Based on regression functions, the results showed that the power output of the PV green roof was 1.3% higher than the power output of the PV-black roof in Phoenix, AZ. In the present study, the power output of the PV-green roof at 18 cm height was 1.16% higher than the power output of the PV panel above the black roof, which was EPDM. Therefore, these results are comparable to the results of Nagengast.

Another important experimental study was that of Chemisana and Lamnatou [57]. Three small scale roof configurations, which were PV-sedum, PV-gazania and PV-gravel, were tested during the period of June through July, 2013, at the University of Lleida. The results of the PV-gazania vs. PV-gravel test showed that the average maximum power output of the PV-gazania was 1.29% higher than that of the PV-gravel while the average increase was 1.15%. In the present study, the average maximum power output of the PV-green roof was 1.26% higher than that of the PV-black roof while the average increase was 1.16%, which is comparable to the findings of the Chemisana and Lamnatou. We compare this result with the PV-gazania scenario and not with the PV-sedum, because the gazania and the dianthus, which was used in the present study as a green roof, have flowers and narrow leaves. However, the sedum is a succulent that has thick leaves. Moreover, in Chemisana and Lamnatou's study, the results showed that the sedum improved the incident irradiance on the PV panel by 1.41% more than the gazania. The PV-sedum generated 2.24 % more electricity than the PV-gazania.

Another experimental study was that of Perez et al. [56]. Multiple small scale roofing systems, including gravel, PV-gravel, green, and PV-green, were tested in New York. The type of the plant employed in this test was a sedum. The results showed that the PV-green roof produced 2.56% more electricity than the PV- gravel roof in June 2011. In the present study, as mentioned above the PV-green roof outperformed the PV-black roof by 1.16%. The 1.4% higher value of Perez' study might be due to the difference in the type of plant and the difference in the weather conditions [61]. Furthermore, this higher value might be due to the difference in the size of the panels because when the size of the panel decreases, the heat transfer coefficient increases [62]. This leads to an increase in the power output due to decreasing the temperatures of panels.

Finally, the results presented by Hui and Chan [50] cannot be compared appropriately because a sedum green roof was used in this study. As mentioned above, the sedum increased the incident irradiance on the PV panel by 1.41% more than the gazania which is similar to the dianthus. Moreover, the climatology in Hong Kong is different from that of Portland [63]. In addition, this study was only for three hours on a sunny day. For this point, it is important to note that the PV-green roofs are more beneficial than PV-conventional roofs when ambient temperatures are higher than 25˚C [55].

Chapter 4: Discussion of Experimental Results

Regarding the results described in Chapter 3, the mean temperature of the PV-green roof was lower than the mean temperature of the PV-black roof due to three factors. Firstly, the albedo of the green roof is higher than the albedo of the black roof. As a result, the green roof surface would be cooler than the black roof surface, and the green surface would increase the incident radiation on the PV panel. Secondly, the PV- green roof was cooler due to the effect of the evapotranspiration from the soil and plants, and that increased the cooling effect. Finally, the heat transfer coefficient of the PV-green roof was higher than that of the PV-black roof due to the effects of the plant canopy on the heat transfer coefficient. When the heat transfer coefficient increases, the temperature decreases. One of the factors that affects the convective heat transfer is the roughness of the surface. If we have two surfaces that are different in the roughness, the convective heat transfer of the surface that is rougher is higher than the less rough under the same flow [64]. The rough surfaces increase turbulent mixing (beneficial effects in our case). Thus, it is understandable that the heat transfer coefficient of the PV-green roof was higher than that of the PV-black roof due to the roughness of the green roof surface. As a result, the power output of the PV-green roof was higher than the power out of the PV-black roof.

In the case of the PV-green roof vs. the PV-white roof, the temperature of the PV-green roof was lower than the PV-white roof for the same reasons described above, with the exception of the albedo. Although the albedo of the white roof is higher than the albedo of the green roof, the effect of the roughness and the evapotranspiration of the vegetated green roof was higher than the effect of the albedo. In the results section, it was noted that the PV-green roof was 3.0˚C cooler than the PV-white roof while the PV-green roof was 2.5˚C cooler than the PV-black roof due to different weather conditions between the two experiments. Based on the temperature difference between the PV-green vs. the PV-white roofs and the temperature difference of the PV-green vs. PV-black roofs , the difference in power output for the PV-green vs. PV-white roofs should be higher or the same as the power output of the PV-green vs. PV-black roofs. However, the results showed that the PV-green roof generated 1.16% more electricity than the PV-black roof while the PV-green roof generated 0.75% more electricity than the PV-white roof. This could be due to the high reflectivity of the white roof (works as a reflector). The white roof sent more light to the PV panel and that contributed to the increase power output.

In the PV-white roof vs. PV-black roof experiment, the temperature of the PV-white roof was lower than the temperature of the PV-black roof due to reasons mentioned above. In addition, the emissivity of the black roof was higher than the emissivity of the white roof and the mean temperature of black roof surface was 3˚C higher than the temperature of the white roof surface. Thus, the longwave radiation from the black roof to the PV panel was higher than that of the white roof. Thus, the PV-white roof outperformed the PV-black roof by producing 0.7% more electricity.

Regarding the raising of the PV-panel, as mentioned previously, due to structural constraints, we were not able to simultaneously test panels at two different heights. Thus, we monitored panel performance first with both panels set to the 18 cm height and then conducted the same experiments with the panels set at the 24 cm height. It should be noted that there was a performance improvement in all scenarios. In the case of the green roof, the temperature of the PV-green roof at 24 cm height was 1.4˚C cooler than the PV-green roof at 18cm height. This difference could be related to the heat transfer coefficient. The mean heat transfer coefficient of the 24 cm PV-green roof was 8% higher than the mean heat transfer coefficient of the 18 cm PV-green roof. This higher heat transfer coefficient could be due to more airflow passing under the PV panel when the PV panel was raised. The heat transfer coefficients are directly proportional with the wind speed. In addition, when the wind speed increases, the rate of evaporation increases and this improves the cooling effect, thus decreasing the temperature of the PV panel. It is important to choose the reasonable distance between the PV panel and the green roof because placing the PV panel far away above the green roof might reduce the cooling effect of the evapotranspiration on the PV panel. Furthermore, it is significant to note that the evapotranspiration contributes considerably to cool the microclimate.

In the case of the black roof, it is clear that the temperature of the 24 cm black roof was 1.15˚C cooler than the 18 cm PV-black roof. This difference was due to two factors. Firstly, the mean heat transfer coefficient was higher in the case of the 24 cm PV-black roof because the wind speed under it was higher than that of the 18 cm PV-black roof. Secondly, the effect of the black roof on the PV panel reduced when the PV panel was raised. As a result, the mean power output of the 24 cm PV-black roof was higher because the power output is inversely proportional with temperature of the PV panel.

Chapter 5: Conclusion

The combination of green roofs with the PV panels has been experimentally studied to investigate the effect of changing the height of the PV panel from the roof on the PV temperature and performance. This included studying how the heat transfer coefficient varies with the height and the effect of the vegetation layer on the heat transfer coefficient. The experiment was conducted at two heights (18 and 24 cm), both measured as the spacing between the roof surface and the lower edge of the PV panel. Also, the goal of this study was to investigate the effect of the underlying roof type on the performance of a roof integrated PV system. Three roof configurations; PV-green roof, PV-black roof and PV-white roof were tested on the roof of STRC Building at Portland State University in Portland, Oregon. Based on the experimental data that were collected from July 18 to September 15, 2014, the roofing systems described above were evaluated.

The results showed that the green roof has a positive effect on the PV electrical performance. The PV-green roof produced 1.16% more electricity than the PV-black roof at 18 cm height and 1% more electricity at 24 cm height. Furthermore, the PV-green roof generated 0.75% more electricity than the PV-white roof at 18 cm height and 0.68% more electricity at 24cm height. The PV-white roof produced 0.70% more electricity than the PV-black roof at 18 cm height and 0.44% more electricity at 24 cm height. The results of the power output differences in all the experiments were statistically significant with a 95% confidence interval ($P < 0.01$).

These results were compared with multiple experimental studies and consistencies were found in the power output differences. Results from Nagengast et al. [55], and Perez et al. [56], and Chemisana and Lamnatou [57] found the PV panel above green roofs performed roughly 0.5 to 3% better than the PV panel above variations of conventional roofing. A second set of studies, including work by Hui and Chan [50] and Köhler et al. [53] found that the green roof benefit was in the range of 4 to 8% power output improvement relative to conventional roofing. Based on the results from the present study, we find the green roof benefit to be in the general range of 1% increase in PV output depending upon conditions and installation characteristics. We hypothesize that the much larger benefits suggested by some studies may be due to experimental inconsistencies such as comparison of installations with fundamentally different height placements above the underlying roof. In any case, further investigation is justified to develop a more thorough understanding of why some systems appear to perform better than others and how PV-green roof systems can be optimized.

In terms of the temperature and the heat transfer coefficient of the PV panel, the results revealed that PV-green roof mean temperatures were 2.5˚C and 3˚C lower than the mean temperatures of the black and white roofs at 18 cm height and 1.8˚C and 1.5˚C lower at 24 cm height, respectively. The mean temperatures of the PV-white roof were 1.3˚C lower than the PV-black roof at 18 cm height and 0.83˚C lower at 24 cm height. The mean heat transfer coefficients of the PV-green roof were 23% and 20% higher than the mean heat transfer coefficient of the PV-black roof and the PV-white roofs at 18 cm height and 10.2% and 7% higher at 24 cm height, respectively. It is important to note that limitations in the available sensors and monitoring equipment required conducting experiments involving two test surfaces at a time. This accounts for the differences in the values due to the different weather conditions during each test. The mean heat transfer coefficients of the PV-white roof were 6.7% higher than the mean heat transfer coefficient of the PV-black roof at 18 cm height and 2% higher at 24 cm height.

In terms of using the same panel and the same roofing type at different heights, the local weather station was used as a reference to determine similar weather conditions to compare the PV performances between the two heights. The results showed a positive impact on the PV panel performance when the PV panel was raised. When using the green roof under the PV panel, the mean power output of the 24 cm PV panel was higher than the mean power output of the 18 cm PV panel. Moreover, the heat transfer coefficient of the 24 cm PV-green roof was 8% higher than the mean heat transfer coefficient of the 18 cm PV-green roof. In the case of using the black roof under the PV panel, the mean power output of the 24 cm PV panel was higher than the mean power output of the 18 cm PV panel. In addition, the mean heat transfer coefficient of the 24 cm PV-black roof was 12.2% higher than the mean heat transfer coefficient of the 18 cm PV-black roof.

The results of this study showed another positive effect of the combination of the PV panels with green roofs on the environment. The temperatures of the soil surface of the green roof was 14.8˚C and 13.5˚C lower than the temperature of the black roof and white roof surfaces, respectively. This will decrease summer heat conduction into the building, lowering air conditioning demands [54], and provide potential benefits with respect to mitigation of the Urban Heat Island effect as suggested in the Scherba et al. study [49].

The present study demonstrates the value of integrating PV panels with green roofs and provides some guidance regarding optimization of such combined systems. Specifically, it has been shown that raising the PV panels has a positive effect on the PV performance. It would be helpful, however, if additional studies were conducted to include long-term measurements to evaluate the annual performance using multiple roofing types at different heights simultaneously.

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