CONVENTIONAL & GREEN ROOF ALBEDO MEASUREMENT AND ANALYSIS FOR ROOF-MOUNTED PHOTOVOLTAIC APPLICATIONS

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Abstract

In this work a low-cost integrating sphere is designed and constructed, for the purpose of measuring the albedo of a variety of roofing materials. The albedos of roofing materials including asphalt shingles, black polymer roofing material, green roof soils, and green roof plants are measured. Reflectivity data is referenced to a commercial high-reflectivity white-roof sample, generating a reflectance ratio across the visible and infrared spectra for each sample. Absorptance spectra are also generated from the reflectivity data by using the Kubelka-Munk equation. A statistical error analysis is used to determine a wavelength range for which data is acceptable to 95% certainty. Reflectivity data is compared with performance data of copper indium gallium diselenide (CIGS) photovoltaics, to evaluate the appropriateness of various roofing materials for application with roof-mounted cylindrical photovoltaics.
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1 Background

The potential for positive interaction between green roofs and roof-mounted solar cells motivates this research, in which the relative reflectivity of various roofing materials, including green roofs, is to be determined. Previous studies (Kohler et al., 2002) indicate that the synthesis of photovoltaics and green roofs generates positive effects in terms of both the health and viability of the green roof plants, and the efficiency of the photovoltaic system. The former effect, namely the increase in green roof health, is due to the partial shading supplied by the photovoltaics, which has proven more conducive to plant growth. The latter effect comes about because of the evaporative cooling effects of green roofs. Photovoltaic modules experience a drop in efficiency at elevated module temperatures, temperatures that are easily attained, on clear days, on systems mounted over conventional concrete or asphalt shingle roofs (Krauter & Hanitsch, 1996). Green roofs, however, offer the ability to lower the temperature of photovoltaic modules mounted directly above them through evaporative cooling, thereby increasing photovoltaic module efficiency.

The Pennsylvania State University regularly constructs a solar home for entry into the biannual U.S. Department of Energy Solar Decathlon. *Natural Fusion*, the home entered by Penn State into the 2009 competition, employed an innovative integrated green roof and photovoltaic module design. Horizontal rows of cylindrical copper indium gallium diselenide (CIGS) photovoltaic cells were mounted above a green roof. This design allowed some sunlight to reach the green roof and be reflected back toward the underside of the cylindrical photovoltaic modules. Thus, the temperature of the photovoltaic modules was moderated via evaporative cooling from the green roof, increasing photovoltaic module efficiency. However, the tradeoff in this case was a lower reflectivity of the green roof as compared to an ideal white roof, resulting in less light reflection onto the underside of the modules. This study, intended to assist with future system integrative photovoltaic designs, aims to determine the relative reflectivity, across the visible and near-visible spectrum, of various green roof and conventional roof samples. This knowledge is critical for selecting the roofing material to be employed when solar modules are mounted above roofs.
Additionally, this work demonstrates an inexpensive means of creating an optical integrating sphere, with solar simulator lamp and spectrometer, for the purpose of measuring visible and near-visible reflectance for any material, including whole plants or plant clusters. The sphere is unique in its exceptionally low cost, as well as in its transportability; it can be moved and simply set atop any sample whose reflectivity is to be measured. Thus, this integrating sphere eliminates the need to remove samples from their natural environment.

Previous work has focused on measuring the reflectance of a single leaf of a given plant, rather than taking measurements on a whole plant or plants growing in typical green-roof soil or gravel. Past studies (Major et al., 1993) have found that there is a wide variation of reflectivities among differing plant species, even for individual leaves mounted at a uniform angle; differences in reflectivity for whole plants that differ structurally are expected to be even greater. Thus, for the application of solar modules mounted above green-roofs, it is critical to determine both the reflectivity and the evaporative cooling capability of the specific whole plants or plant mixes under consideration, in order to determine the optimal plant or plants to be employed. This work seeks to answer the first part of this puzzle, i.e. to determine the reflectivity of whole plants, growing atop green-roof soil, and to compare this to the reflectivity of a variety of conventional roofing material samples.


2 Literature Review

2.1 Green-Roof Reflectivity

The aim of this study is to find reflectance spectra for a range of roofing materials, including common green roof plants and their associated soils/gravels. This information can be combined with data or modeling on the cooling capacity of green roofs in studies to be conducted in the future, in order to determine the practicality of pairing solar cells with green roofs. Research on the reflectivity of roofing materials in the past has been substantial; however, reflectivity data on green roofs is very limited. Previous plant reflectivity studies have generally involved either the isolation of a single leaf of the plant in question and the determination of its optical properties (Rebelo-Mochel & Ponzoni, 2007), or macroscopic measurements of plant canopy albedo taken by satellite imagery (Alton, 2009). Neither of these strategies is as relevant to green roof reflectivity studies as the examination of the optical properties of a whole plant or plant cluster surrounded by green-roof soil or gravel, as is performed in this study.

The work of Rebelo-Mochel and Ponzoni (2007) measured the reflectivity of single mangrove leaves with an integrating sphere. The intensity of light measured at the spectrophotometer (Spectron SE-590) when a leaf was placed in the sphere was compared with the intensity when a barium sulfate-covered reference plate replaced the leaf. For four species of mangrove, the sample reflectivity divided by the reflectivity of the barium sulfate plate varied from 0.05 to 0.45 between 350 and 1100 nm. The highest reflectivity occurred for light wavelengths around 900 nm, and the lowest reflectivity around 500 nm, as shown in Figure 1 (note that Directional Hemispherical Reflectance Factor (DHRF) is reflectance of leaf divided by reflectance of barium sulfate plate):
A study by Major et al. (1993) found significant differences in the reflectance of single leaves of maize, beans, wheat, and senesced potato, especially at wavelengths below 760 nm. At wavelengths above 760 nm, single leaf reflectance levels out at a value much higher than the visible light reflectivity. This infrared reflectivity is approximately equal to 0.45 for the beans, wheat, and senesced potato species measured, while it drops to just above 0.4 for the maize. The reflectances, as measured with an integrating sphere, are shown by the solid lines in the four graphs that constitute Figure 2.
Daughtry et al. (2000) determined the effects of chlorophyll concentration in corn leaves on reflectivity; reflectivity increased with chlorophyll concentration for 800 nm light but decreased for shorter wavelengths including 715 nm, 670 nm, and 550 nm, as seen in Figure 3. Furthermore, the chlorophyll concentration is correlated positively with the degree of nitrogen fertilization. Thus it seems that for applications on green roofs with mounted solar cells, plants could conceivably be fertilized to increase the reflection of light onto the solar cells.
A study by SuHong et al. (2008) has shown that plant reflectivity can also be altered by the addition of copper pollutants to the soil. The addition of copper sulfate to the soil in which *Brassica Campestris* L. was growing resulted in substantially increased reflectivity in the visible wavelengths (up to a 0.15 albedo increase near 550 nm wavelength), and decreased reflectivity in the near-infrared wavelengths. Note that measurements were taken on single leaves.

Genetic engineering of plants to increase albedo has recently been suggested as a means of moderating global climate change by increasing the amount of solar radiation that is reflected away from the earth’s surface (Ridgwell et al., 2009). Specifically, Ridgwell et al. suggest genetic modification to alter the structure and thickness of the waxy (glaucous) layer covering many leaves, to increase reflectivity. Ridgwell et al. predict that a 40% increase in plant canopy albedo might reduce global surface air temperature by more than 0.2 K, relative to a reference case with high carbon dioxide concentrations and no increase in canopy albedo.

Figure 3: Percent diffuse reflectance vs. chlorophyll concentration at selected wavelengths. Note: y-axis varies from 0% to 50%. (Daughtry et al., 2000)
2.2 Copper Indium Gallium Diselenide (CIGS) Solar Cell Performance

The quantum yield, or ratio of electrons generated to photons absorbed, for CIGS solar cells is plotted in a study by Ramanathan et al. (2005) (See Figure 4). From past plant reflectivity studies, it seems that while reflectivity from plants in the visible spectrum is fairly low, reflectivity of wavelengths greater than ~700 nm is much higher. Fortunately, CIGS cells convert photons to electricity quite effectively up to 1000 nm wavelength or slightly beyond.

![Figure 4: Quantum yield of CIGS solar cells. (Ramanathan et al., 2005)](image)

A study by Del Cueto (2002) shows that for all types of photovoltaic modules tested, there is a considerable decrease in module efficiency as temperature increases, as shown in Table 1. The numbers given are percent of original efficiency per degree Celsius (C) temperature change; it is important to note that the figures are not in terms of absolute efficiency, but in terms of percent of initial efficiency. Thus, for the module types listed in Table 1, namely crystalline silicon (c-Si), polycrystalline silicon (pc-Si), cadmium indium diselenide (CIS), and cadmium telluride (CdTe), a temperature change of 30 degrees C would result in an absolute efficiency reduction of 1-2% (Del Cueto, 2002).

Accordingly, it is clear that for most commercial photovoltaic technologies, the control of module temperature is essential for maintaining maximum efficiency, and green roofs may hold promise as a means of cooling roof-mounted cells.

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>c-Si</th>
<th>c-Si</th>
<th>c-Si</th>
<th>pc-Si</th>
<th>pc-Si</th>
<th>CIS</th>
<th>CdTe</th>
</tr>
</thead>
<tbody>
<tr>
<td>%/°C</td>
<td>-0.496</td>
<td>-0.388</td>
<td>-0.427</td>
<td>-0.401</td>
<td>-0.431</td>
<td>-0.484</td>
<td>-0.035</td>
</tr>
</tbody>
</table>

Table 1: Percent decrease in efficiency (in terms of percent of initial efficiency) per degree Celsius increase in temperature for a variety of photovoltaic module types. From Del Cueto (2002).
2.3 Roofing Material Reflectivity

A study by Bretz and Akbari (1997) measured the albedo of typical highly reflective white roofing materials. Measurements were taken over extended time periods while the sample roofs were exposed to the elements, in order to determine how well these roofs were able to resist dirt and wear and maintain high albedo. The procedure used for reflectivity measurements by Bretz and Akbari is described below:

“Laboratory measurements of hemispherical spectral reflectance were made with a double beam spectrophotometer with integrating sphere. The integrating sphere is a 150 mm diameter sphere surfaced with reflectance material that gives the highest diffuse reflectance of any known material or coating over the UV-VIS-NIR region of the spectrum.” (Bretz & Akbari, 1997)

Bretz and Akbari conclude that their highly-reflective white roof coatings generally have an albedo in the range of 0.6 to 0.8 when clean, but experience a drop in albedo of about 0.15 after one year of exposure to the elements. This is a comparative advantage for green roofs, since their reflectivity, while lower than that of a white roof, should remain fairly constant over time.

Takebayashi and Moriyama (2007) list relevant albedo values of 0.17 for bare soil, 0.15 for a green lawn, 0.37 for concrete, 0.36 for high-reflectivity gray paint, and 0.74 for high-reflectivity white paint. It is surprising to note that the albedo of a green lawn is slightly lower than that of bare soil, which visually appears to be the more absorptive of the two. In a study of green roof soils typical of the western USA, Sailor et al. (2008) found that thermal emissivity was practically constant at 0.96 regardless of soil composition or moisture level. However, albedo decreased with moisture level for all samples. Dry pumice-based soils ranged from 0.28-0.41 (all pumice soils had albedo ~0.4, except when 10% compost was added, which dropped albedo to 0.28); dry shale-based soils ranged from 0.17-0.19. Sailor et al. also note that albedo will change over time with soil settling, and that the albedo of the surface will be “dominated by the relatively coarse aggregate” (Sailor et al., 2008).
A very innovative and practical approach to comparing green roofs to conventional building materials in terms of cooling value is employed Gaffin et al., who argue that the “equivalent albedo” of a green roof (computed as the albedo required of a white roof to obtain the low surface temperatures of a green roof) is 0.7-0.85. Note that based on Bretz and Akbari’s results, it seems impractical to maintain a white roof with an albedo this high after a year of use. Therefore, it seems difficult to obtain the low temperatures characteristic of green roofs by using a white roofing material. The results of Gaffin et al. are plotted graphically in Figure 5.

Figure 5: Infrared emissivity/reflectivity vs. solar reflectivity/absorption for common building materials (Florida Solar Energy Center), with a theoretical depiction of green roofs, based on their cooling performance. From Gaffin et al.
3 Experimental Design and Setup

3.1 Materials

The construction of an integrating sphere at low cost was a key part of this project, and was accomplished successfully, given that a sphere was constructed at a cost one order of magnitude less than the price of a commercial sphere. Components of the sphere included:

- Hollow Styrofoam sphere of 2 ft outer diameter, with a wall thickness of 7/8 in. (www.plasteelcorp.com)
- Approximately 40 ft of angle iron, with regularly spaced bolt holes and slots.
- An Ocean Optics HR2000 spectrophotometer, with DAQ run through SpectraSuite.
- A 12 V / 36 W solar simulator lamp, intended to replicate the emission spectrum of an object at a temperature of 5000 K.
- A 12 V power supply associated to the solar simulator lamp.
- Approximately 2 ft of 4-inch schedule 40 PVC piping, and 3 ft of 2-inch schedule 40 PVC piping, as well as a 4 in X 2 in reducer.
- Two cardboard “washers” with 4 in outer diameters and 1.3 in inner diameters, used as baffles to reduce light intensity and to increase uni-directionality of light entering the sphere.
- Assorted bolts, nuts, and washers, and U-clamps.
- Pure White Gloss Rust-oleum Universal spray paint.

3.2 Lab design

The goal of constructing a low-cost, lightweight, and readily transportable large-diameter integrating sphere was accomplished by using a Styrofoam sphere. However, the Styrofoam lacked the structural robustness to support the spectrophotometer head and especially the solar simulator lamp and its housing. Thus, it was necessary to construct an angle iron support structure (similar to a cube) around the Styrofoam sphere, to hold the lamp, pointed vertically downward, at the top of the sphere.

Three holes were drilled in the Styrofoam sphere, one each for the solar simulator lamp, the spectrophotometer head, and the sample. The sample hole, of 6 in diameter, was cut
at the bottom of the sphere, such that the sphere could be set atop any surface whose reflectivity was to be measured. The spectrometer head hole (0.25 in diameter) was drilled 90° up from the bottom, at the equator of the sphere, while the solar simulator lamp hole (4.5 in diameter) was drilled 90° up from the spectrometer head hole, at the top of the sphere, as shown in Figure 6.

![Figure 6: Integrating sphere setup.](image)

The solar simulator lamp was mounted atop a truncated plastic disc fixed to the inside wall of the 4 in PVC piping housing. The lamp was mounted approximately 3 in from the end of the PVC pipe, and was centered within the pipe. Two cardboard disc baffles were mounted in the PVC pipe, directly in front of the lamp, with a spacing interval of roughly 1 in. The baffles, as well as all exposed PVC surfaces inside of the sphere, were painted with white Rust-oleum paint.

The solar simulator lamp hole was cut to be slightly undersized, such that the sphere could slide up and down the PVC piping, while still remaining firmly sealed around the piping. This vertical motion allowed for the easy placement and removal of samples beneath the sphere. A hole was precision-drilled for the spectrometer head, such that the head could be press-fit into the sphere, with minimal stress on the sensitive head and the associated fiber optic cable. The spectrometer head was connected with a 5 ft length of fiber optic cable to the spectrometer, which transferred data via USB to a laptop computer running SpectraSuite.
3.3 **SolidWorks Modeling**

Prior to the start of construction, a model of the integrating sphere, angle iron support structure, and solar simulator lamp housing was created using SolidWorks. This was done to ensure that there would be no interference of parts and that the samples could easily fit beneath the apparatus (see Figure 7). The lamp mounting apparatus was also modeled, to ensure a straightforward machining process, as shown in Figure 7.

![SolidWorks model of integrating sphere assembly and detail of lamp mounting assembly](image)

*Figure 7: SolidWorks model of integrating sphere assembly (left), and detail of lamp mounting assembly (right).*

3.4 **Experimental Procedure**

All measurements were taken with SpectraSuite running in *Scope* mode, resulting in light intensity vs. wavelength spectra for each sample, with intensity measured in the undefined unit of “counts”. For this reason, it was necessary to reference all spectra against a white sample. Generally, a nearly perfectly white barium sulfate blank is used as the reference sample (Rebelo-Mochel & Ponzoni, 2007). However, it is only logical to use a barium sulfate reference sample when the interior of the integrating sphere is painted with barium sulfate or a similarly reflective (reflectivity > 0.99) material. Since
these coatings are extremely costly, it was decided that no high reflectivity coating would be employed, and instead the white Styrofoam surface would be left bare. Since the interior of the sphere was not of extremely high (>0.99) reflectivity, it was illogical to use a barium sulfate blank as a reference. Instead, all measurements were referenced against a white roof sample (Carlisle’s Sure-Weld 60 mm thickness TPO Membrane). This was done because the important information to be gained from this research is a comparison of the reflectivities of various roofing materials in relation to each other, rather than an absolute reflectance value for each material. For such a comparison, a commercial white roof was the most logical benchmark.

The first two spectra to be measured were the white reference spectra (W) and the dark noise spectrum (D). For the white reference spectrum, the white roof sample was placed beneath the sphere, all ambient lighting was turned off, the solar simulator lamp was turned on, and a spectrum was immediately measured. For the dark noise spectrum, all ambient lighting and the solar simulator lamp were left off, and a spectrum was measured. Each sample was then measured in a similar fashion, with ambient lighting off and solar simulator lamp on, and the sample spectrum (S) was processed using the following equation, in order to reference against the white roof sample and to remove any ambient light effects:

\[
\text{Reflectance Ratio} = \frac{S-D}{W-D} \quad (Eq. \ 1)
\]

For all measurements, the sample was slid under the bottom of the integrating sphere, and the sphere was lowered as far as possible, creating as tight of an optical seal as possible. It was discovered, however, that the plant and soil samples allowed much more leakage of light around the rim than did the reference white roof sample, since the plant and soil surfaces were relatively uneven compared to the perfectly smooth white roof sample. For this reason, when taking the white roof reference spectrum, it was necessary to lay a 6 in disc of the white roof sample over a flat but relatively uneven soil sample, to obtain a reference with light leakage more similar to that observed when the other samples were measured. A photograph of the completed experimental setup is shown in Figure 8.
3.5 Experimental Error Analysis

It was clear from the data that significant scatter and error was present at the high- and low-wavelength ends of the spectrum. This was assumed to be due to the low light intensity emitted by the solar simulator lamp at the far ends of the spectrum, as shown in Figure 9, which is the reflectance spectrum of the white roof reference sample. This spectrum is an approximation of the intensity spectrum of the light emitted by the solar simulator lamp.
The very low intensity of the light at the left and right ends of the spectrum was thought to cause the large scatter seen in the reflectance ratio data, as the spectrophotometer sensor requires a minimum light intensity for accurate measurement. Also, Eq. 1, which has the white roof reference spectrum, \( W \), in the denominator, shows that the error function of the lamp and spectrophotometer can be approximated as Eq. 2.

\[
\text{Error Function} \approx \frac{1}{W} \quad (E\text{q. 2})
\]
The error function, along with its 45-pt moving average, is plotted in Figure 10.

![Figure 10: Solar simulator lamp - spectrophotometer error function (Eq. 2). Raw data is in black, while a 45-pt. centered moving average is in red.](image)

It is evident that the scatter in the data, visible as the divergence of the raw data from the 45-pt. moving average, increases noticeably at right and left ends of the graph. In order to quantify this divergence, a graph of residuals between the data and the moving average was plotted in Figure 11. The standard deviation of the residuals was then calculated, and found to be $\sigma = 6.2156 \times 10^{-5}$, while the mean of the residuals was found to be $6.4014 \times 10^{-7}$. Allowing a maximum residual of $\pm 2\sigma$ about the mean, for a 95% confidence interval, we find that the maximum allowable residual bounds are $-1.111 \times 10^{-4}$ and $+1.131 \times 10^{-4}$. These limits are breached at 415.87 nm and 860.09 nm, thus data outside of these wavelength bounds is not acceptable with 95% confidence. Figure 11 shows the residual plot along with two vertical lines that demarcate the acceptable data, namely the data between 415.87 nm and 860.09 nm.
Figure 11: Residual graph. Data acceptable to 95% certainty is bounded on the left by the vertical line at 415.87 nm and on the right by the vertical line at 860.09 nm.

Thus, a statistical analysis of the error function residuals yielded a wavelength range for which the data presented herein is acceptable to 95% certainty. The graphs of data presented in the Appendix section show increased scatter at wavelengths near those found here, but it is difficult to know at what point the data becomes unacceptable; this analysis gives a precise cutoff beyond which data is not useful, and the results presented in Section 5.1 show only the useful range of data.
4 Selection of Samples

4.1 White (Reference) and Black Roof Samples

The white (reference) roof sample was a commercially available polymer membrane, Carlisle’s Sure-Weld 60 mm thickness thermoplastic olefin (TPO) Membrane. The black roof sample was a single-ply commercial polymer membrane.

4.2 Green-Roof Samples

The green roof samples can be divided into two categories: the single plant samples with no exposed bare soil, and the mixed plant samples with varying degrees of exposed bare soil. The former group consisted of four species of the Sedum genus, as Sedum plants are presently the predominant species used in green roofs (Oberndorfer et al., 2007). The four species measured individually were Sedum Album, Sedum Hispanicum, Sedum Sexangulare, and Sedum Sarmentosum. These samples all were in good health, showed dense ground coverage, and had no weeds. All four samples are shown in Figure 12.

Figure 12: Single plant samples. Clockwise from top left: S. Sexangulare, S. Spurium, S. Hispanicum, S. Album.
The latter group consisted of five samples of mixed green roof plant growth. These were spots measured on pallets used on a green roof, and thus were representative of actual growing conditions, including bare soil patches and occasional weeds. The first sample area consisted of a *Dianthus Barbadus* plant surrounded by low-lying *S. Sarmentosum* and limited bare soil, as shown in Figure 13.

Figure 13: Mixed Sample 1: Mixed *D. Barbadus* (center) and *S. Sarmentosum* sample.
The second sample consisted of mixed *S. Spurium* and *S. Sexangulare*, with a limited area of bare soil, as shown in Figure 14.

![Figure 14: Mixed Sample 2: Mixed *S. Spurium* (left) and *S. Sexangulare* (right) sample.](image)

The third sample consisted of a mix of four green roof plants: *Sedum Floriferum*, *S. Album*, *S. Spurium*, and *Delosperma Nubigenum*, as shown in Figure 15.

![Figure 15: Mixed Sample 3: Mixed *S. Floriferum* (left), *S. Album* (top), *S. Spurium* (top right), and *D. Nubigenum* (bottom right) sample.](image)
The fourth sample consisted of a sparse mix of *Sedum Reflexum* and *S. Floriferum* with a sizable bare soil area exposed, as shown in Figure 16.

![Figure 16: Mixed Sample 4: Mixed *S. Floriferum* (left) and *S. Reflexum* (top) sample.](image)

Finally, the fifth sample consisted of a mix of *S. Sarmentosum* and *S. Album*, with small areas of *Oxalis* weed growth and bare soil, as shown in Figure 17.

![Figure 17: Mixed Sample 5: mixed *S. Sarmentosum* (left), *S. Album* (right), and weed *Oxalis* (scattered, top left) sample.](image)
The composition of each of the five mixed samples is detailed in Figures 13-17 and is summarized in Table 2.

<table>
<thead>
<tr>
<th>Mixed Sample #</th>
<th>Sample Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed Sample 1</td>
<td><em>D. Barbadus</em> and <em>S. Saramentosum</em></td>
</tr>
<tr>
<td>Mixed Sample 2</td>
<td><em>S. Spurium</em> and <em>S. Sexangulare</em></td>
</tr>
<tr>
<td>Mixed Sample 3</td>
<td><em>S. Floriferum</em>, <em>S. Album</em>, <em>S. Spurium</em>, and <em>D. Nubigenum</em></td>
</tr>
<tr>
<td>Mixed Sample 4</td>
<td><em>S. Floriferum</em> and <em>S. Reflexum</em></td>
</tr>
<tr>
<td>Mixed Sample 5</td>
<td><em>S. Saramentosum</em>, <em>S. Album</em>, and <em>Oxalis</em></td>
</tr>
</tbody>
</table>

### 4.3 Soil Samples

Three soils/gravels used as green roof bedding material were tested: a brown gravel with low pearlite concentration, the same brown gravel with high pearlite concentration, and a grey gravel with no pearlite. Additionally, the reflectivity of a sample of pure pearlite was measured.

### 4.4 Asphalt Shingle Samples

Four commercial asphalt shingle samples were tested. These included two varieties of white shingle, as well as a black and brown shingle sample. These four samples represented a broad cross section of conventional roofs used in contemporary homes.
5 Results and Discussion

5.1 Experimental Data

Reflectance spectra are plotted in terms of reflectance ratio vs. wavelength in Figures 18-22, where reflectance ratio is as defined in Eq. 1. The x-axis for all data runs from 416 nm to 860 nm, as this is the useful data range found in Section 3.5. One spectrum was taken for each sample, and the data was compiled on four plots. The data has been divided into four groups, namely black roof sample & asphalt shingles, green roof soils & pearlite, single green roof plant samples, and mixed green roof samples. As a baseline, the reflectivity ratio of the black asphalt shingle sample is plotted on all graphs, and is plotted alone in Figure 18.

![Figure 18: Reflectance ratio of the black asphalt shingle, used as a baseline and plotted on all reflectance ratio graphs. Note: while reflectance ratio can vary from 0 to 1, the y-axis is set to vary from 0.3 to 0.8.](image)
The reflectance ratio plot of the black roof sample and the asphalt shingles is shown in Figure 19.

![Figure 19](image19.png)

**Figure 19**: Reflectance ratio of black roof sample and assorted shingles. Note: while reflectance ratio can vary from 0 to 1, the y-axis is set to vary from 0.3 to 0.8.

The reflectance ratio plot of green roof soils and pearlite is shown in Figure 20.

![Figure 20](image20.png)

**Figure 20**: Reflectance ratio of assorted green roof soils and pearlite. Note: while reflectance ratio can vary from 0 to 1, the y-axis is set to vary from 0.3 to 0.8.
The reflectance ratio plot of single green roof plants is shown in Figure 21.

Figure 21: Reflectance ratio of four Sedum species commonly used in green roofs. Note: while reflectance ratio can vary from 0 to 1, the y-axis is set to vary from 0.3 to 0.8.

The reflectance ratio plot of mixed green roof plant samples is shown in Figure 22, along with small images of the mixed samples (these are scaled Images 13-17), arranged from top to bottom in the same order as the captions in the graph, i.e. 5-1-3-2-4.
Figure 22: Reflectance ratio of mixed samples, each composed of a mix of two or more typical green roof plants and soil. Note: while reflectance ratio can vary from 0 to 1, the y-axis is set to vary from 0.3 to 0.8. Images of the samples are shown at right, with images arranged from top to bottom in the same order as the in-graph captions, i.e. 5-1-3-2-4.

The Kubelka-Munk function was also generated and plotted for each spectrum, as a means of quantifying absorptance. The Kubelka-Munk function is shown in Eq. 3.

\[
Kubelka - Munk = F(R) = \frac{(1-R)^2}{2R} = \frac{k}{s} = \frac{Ac}{s} \quad (Eq. 3)
\]

Where
R = reflectance ratio
k = absorption coefficient
s = scattering coefficient
c = concentration of the absorbing species
A = absorbance

Plots of a Kubelka-Munk absorptance ratio follow, calculated from Eq. 3 based on the reflectance ratio data collected. The plots are arranged in the same order as the reflectance ratio plots, including the black asphalt shingle first plotted alone and then plotted as a baseline on all other graphs. See Figures 23-27.
Figure 23: Kubelka-Munk absorptance ratio of the black asphalt shingle, used as a baseline and plotted on all Kubelka-Munk absorptance ratio graphs. Note: while absorptance ratio can vary from 0 to 1, the y-axis is set to vary from 0 to 0.8.

Figure 24: Kubelka-Munk absorptance ratio of black roof sample and assorted shingles. Note: while absorptance ratio can vary from 0 to 1, the y-axis is set to vary from 0 to 0.8.
Figure 25: Kubelka-Munk absorptance ratio of assorted green roof soils and pearlite. Note: while absorptance ratio can vary from 0 to 1, the y-axis is set to vary from 0 to 0.8.

Figure 26: Kubelka-Munk absorptance ratio of four Sedum species commonly used in green roofs. Note: while absorptance ratio can vary from 0 to 1, the y-axis is set to vary from 0 to 0.8.
Figure 27: Kubelka-Munk absorptance ratio of mixed samples, each composed of a mix of two or more typical green roof plants and soil. Note: while absorptance ratio can vary from 0 to 1, the y-axis is set to vary from 0 to 0.8. Images of the samples are shown at right, with images arranged from top to bottom in the same order as the in-graph captions, i.e. 4-2-3-1-5.

5.2 Discussion

5.2.1 Plant color vs. reflectance ratio

The spectra of the green roof plants, whether mixed or single, show interesting results. First, a local peak in reflectivity is visible at 550 nm for almost all of the plant samples. This is logical, given the absorptance spectra of chlorophyll a and chlorophyll b, the photosynthetic pigments present in plants. Chlorophyll a shows absorptance peaks at approximately 430 nm & 660 nm, while chlorophyll b shows peaks at approximately 450 nm and 640 nm, where the chlorophyll is in an ether solution (Comar & Zscheile, 1942). These peaks in chlorophyll absorbance correspond well with the reflectivity increase seen in almost all plant samples between 500 and 600 nm. Not surprisingly, the only sample that did not show increased reflectivity between 500 nm and 600 nm was *S. Spurium*, which has a reddish color, as can be seen in Figure 12. As would be expected based on its red color, the *S. Spurium* sample showed a slowly increasing reflectivity towards the longer-wavelength end of the visible spectrum, from 600 nm to 700 nm.
5.2.2 Plant reflectivity and CIGS solar cell performance

Perhaps the most significant finding, for the application of solar cells installed above green roofs, was the sharp increase in reflectivity observed in both the single and mixed plant sample between 700-750 nm, as well as the sustained high reflectivity in the infrared wavelengths (see Figures 21 and 22). While reflectivity of the plant samples in the visible spectrum was measured to be in line with or lower than the reflectivity of the conventional roofing samples, the abrupt increase in plant reflectivity in the infrared wavelengths is unparalleled in any other sample. Even perlite, the most reflective non-plant sample, falls below both *S. Album* and *S. Sexangulare* in terms of infrared reflectivity.

This high infrared reflectivity of the plant samples is promising for roof mounted CIGS solar cell applications for two reasons. The first reason is that since the plant samples absorb comparatively little infrared light, they should remain at a lower temperature than conventional roofing materials under the same insolation. The cooling effect of this high infrared-reflectivity is in addition to the heat loss through evapo-transpiration unique to green roofs (Gaffin et al.), making green roofs ideal for maintaining low surface temperatures on sunny days. The second reason is that the quantum yield curve of CIGS solar cells (see Figure 4) is such that the majority of the electron excitation within the cell (and thus the majority of the electricity generated by the cell) results from radiation above 700 nm in wavelength. Thus, the high infrared reflectivity of the green roof plants, particularly *S. Sedum* and *S. Sexangulare*, is very promising for keeping CIGS cells cool while still supplying a large part of the useful spectrum to the solar cells.

The mixed plant samples exhibited a lower infrared reflectivity compared to the single plant samples; this is likely due to the much higher degree of exposed bare soil in the mixed samples, as none of the soils showed an increase in reflectivity in the infrared range. Furthermore, the degree of infrared reflectance varied considerably within the mixed samples, with Mixed Sample 5 showing the highest infrared reflectivity, and Mixed Sample 4 showing the lowest. Examination of the photographic images of Mixed Sample 4 and Mixed Sample 5 (Figures 16 and 17, respectively) shows that the amount of exposed soil is much greater in Mixed Sample 4 than in Mixed Sample 5, likely accounting for the lower infrared reflectivity of Mixed Sample 4. Thus it would seem
that for roof-mounted solar cell applications, it is very important to maintain near total plant coverage on green roofs, in order to maintain the very high infrared reflectivities observed in the single plant samples, which showed almost total plant coverage.

5.2.3 Light leakage and resulting measurement error

A surprising result worthy of further discussion was the fact that visible wavelength reflection for all of the mixed samples, as well as *S. Spurium*, was measured to be lower than for the Black Asphalt Shingle sample. It seems quite counterintuitive that a visibly colored substance would be less reflective than a black one. A likely explanation for the lower reflectivity readings of the mixed plant samples and *S. Spurium* is leakage of light from the integrating sphere around the perimeter of the sample hole. Any leakage of light from the integrating sphere would result in a lower reflectivity measurement, as any leaked light would be interpreted by the spectrophotometer as having been absorbed by the sample.

There was a very tight seal between the sample hole and the surface of the shingle (and all other non-plant samples), since the sample surface was level and fairly smooth. Thus, practically no light escaped the sphere for these samples. However, the plant samples—particularly the mixed samples—were quite uneven and rough, allowing noticeable amounts of light to leak out from the sphere around the perimeter of the sample hole. The mixed samples likely experienced the most leakage because they contained both bare soil areas and thick plant areas, making a very uneven profile and creating gaps between the sphere and the sample surface. While the *S. Spurium* sample did not have bare soil patches, it nonetheless had a very uneven surface, a sort of web of plant stalks (see Figure 12), that likely resulted in significant light leakage. The other single plant samples likely also experience a small amount of light leakage, but certainly less than the mixed samples and *S. Spurium*, given their smoother surface and the greater structural flexibility of the plants.

In order to verify whether light leakage around the perimeter of the sample hole was causing a significant change in reflectivity measurements, a test was devised using the Black Roof Sample. A circle of the black roofing material was cut to be just smaller than the size of the sample hole, and was laid atop a rough and uneven patch of grey soil sample. The reflectivity of this sample was then measured in the manner described in the
experimental procedure section. A perceptible amount of light was leaked around the perimeter of the sample hole, as a perfect seal was not possible given the uneven soil, thus simulating the conditions for the plant samples. Reflectance ratio data for this sample was plotted on the same graph as the original Black Roof Sample data (which had a tight seal without light leakage). See Figure 28.

Figure 28: Comparison of Black Roof Sample with and without light leakage around the circumference of the sample hole in the integrating sphere.

Figure 28 indicates that light leakage indeed plays a role in reflectivity measurements, particularly in the visible spectrum. It is interesting to note that infrared light seems not to leak from the sphere in the same manner as visible light, (as shown by the higher measured infrared reflectivity of the Black Roof Sample with light leakage), perhaps because of its longer wavelength. Another surprising observation to be made from Figure 28 is that above 900 nm wavelength, the two reflectance ratio curves diverge sharply. Surprisingly, the sample with leakage appears to be much more reflective than the sample without leakage between 900nm to 1000 nm. This aroused suspicions of experimental error, particularly sensor inaccuracy, at very low light intensities. This potential source of error for all of the data is discussed in Section 5.3, where a wavelength range for data acceptable to 95% certainty is established.
6 Future Work

The data acquired in this work are useful as part of a system-level analysis of roof mounted solar cell applications. Future work includes the combination of the reflectivity data presented here with solar cell performance data. This system level analysis should include data on green roof reflectivity (found herein), green roof temperatures, solar cell performance across the visible and infrared spectrum, and solar cell performance at varying temperatures. Obtaining and combining these diverse data sets, and especially modeling of the multi-part system as a whole, is a challenging task that lies ahead.
7 References

_Agricultural and Forest Meteorology_, 149, 17690-1775.

_Energy and Buildings_, 25, 159-167.


8 Appendix: Full-Wavelength Range Data

This appendix includes the full wavelength range of data collected by the Ocean Optics HR2000 spectrophotometer. The x-axis in all graphs in the appendix runs from 150 nm to 1150 nm, in contrast to the graphs presented in the Results section, which run from 416 nm to 860 nm, as discussed in the Experimental Error Analysis section. Note that the y-axis for Reflectance Ratio and Kubelka-Munk Absorptance Ratio graphs runs from 0 to 1.

![Figure 29: White roof reference sample intensity spectrum (approximation of solar simulator lamp spectrum).](image1)

![Figure A2: Reflectance ratio of the black asphalt shingle, used as a baseline and plotted on all reflectance ratio graphs.](image2)
Figure A3: Reflectance ratio of black roof sample and assorted shingles.

Figure A4: Reflectance ratio of assorted green roof soils and pearlite.
Figure A5: Reflectance ratio of four Sedum species commonly used in green roofs.

Figure A6: Reflectance ratio of mixed samples, each composed of a mix of two or more typical green roof plants and soil.
Kubelka-Munk absorptance ratio plots are shown below.

Figure A7: Kubelka-Munk absorptance ratio of the black asphalt shingle, used as a baseline and plotted on all Kubelka-Munk absorptance ratio graphs.

Figure A8: Kubelka-Munk absorptance ratio of black roof sample and assorted shingles.
Figure A9: Kubelka-Munk absorptance ratio of assorted green roof soils and pearlite.

Figure A10: Kubelka-Munk absorptance ratio of four Sedum species commonly used in green roofs.
Figure A11: Kubelka-Munk absorptance ratio of mixed samples, each composed of a mix of two or more typical green roof plants and soil.
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Work Experience
Summer 2009
Project Engineering Intern
ConocoPhillips, Trainer Refinery, Trainer, PA
Supervisor: David Edwards
- Designed and sized pump, control valve, pressure safety valve, and piping for boiler feed-water system
- Developed Request for Quotation and Project Specification for new installations, including a fuel gas coalesce and secondary containment pad
- Performed numerous P&ID checks on new multi-million dollar installations to ensure correct installation
- Corrected an overlooked hydro-test pressure on the day of the test, ensuring safety of plant workers

Summer 2008
National Science Foundation Grant – Undergraduate Researcher
Universidad Carlos III, Madrid, Spain
- Worked with an international team in Spanish
- Conducted research on powdered metals, analyzing the effects of differing heat treatments (sintering/annealing) on various powdered metal alloys
- Employed electron microscopy, X-ray diffraction, Brinell hardness testing

Summer 2006-Fall 2007
Part-Time Undergraduate Researcher
Department of Chemistry, Penn State University
Supervisor: Dr. Thomas Mallouk
- Wrote and published a paper on a new, cheaper and more energy-efficient method for growing TiO₂ nanotubes on a transparent substrate
- Performed anodization and adhesion experiments creating nanostructured materials for use in dye-sensitized solar cells
- Designed and carried out experiments; characterized results using electron microscopy
- Constantly collaborated with other members in very large research group (20+ members)

Spring 2006
Independent Experimental Chemistry Project
Department of Chemistry, Penn State University
- Explored the effects of light intensity on solar cell efficiencies
- Won Best Undergraduate Poster, Penn State Chemistry Sponsors Days 2006, and Best Chem 015 Project, Undergraduate Labs Symposium

Non-Technical Work Experience

Spring 2006
Spanish Instructor
- Taught a group of 8 elementary school children
- Created an innovative 7-week mini-curriculum, with weekly worksheets, emphasizing key verb conjugation and grammar rather than isolated vocabulary

Grants Received:
- Fall 2009: Schreyer Ambassador Travel Grant for semester study in Cairo, Egypt
- Summer 2008: Schreyer Ambassador Travel Grant for work abroad in Madrid, Spain
- Summer 2008: NSF grant for work abroad in Madrid, Spain

Awards:
- Penn State University Evan Pugh Senior Award (awarded to top 0.5% of class)
- PSU President Sparks Award
- PSU President’s Freshman Award
- Best Undergraduate Poster, Penn State Chemistry Sponsors Days 2006

Professional Memberships:
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- Society of Hispanic Professional Engineers

Publications:

International Education:
- Fall 2009: Semester studying Arabic and Egyptology at the American University in Cairo (AUC), Cairo, Egypt

Language Proficiency:
- Fluent in Spanish (Written and Spoken)
- Fluent in French (Written and Spoken)
- Basic Arabic